Problem Definition in Engineering Design:
Using the Universe of Problems Approach to Aid Novice Performance

by

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Submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

at

Dalhousie University
Halifax, Nova Scotia
February, 2022

Dalhousie University is located in Mi'kma'ki,
the ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

This thesis is dedicated to my wife and sons: Erika, Henri, Callum, Joseph, and Adam. Thank you for keeping life interesting and teaching me that life isn't always about going around solving problems.

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ABSTRACT

This thesis describes the importance of the problem definition phase of the engineering design process. The key finding of this study is that when novices are provided with schemes (or design prototypes), their ability to diagnose problems well is dramatically increased. Chapter 2 reviews the literature which explores the culture of engineering and how this culture relates to the practice of problem definition. Chapter 3 surveys the current state of engineering design textbooks regarding problem definition and evaluates several potential tools that can be used in the defining process from the field of Requirements Engineering. Chapter 4 looks again at problem definition, but with a focus on *the nature of a problem itself*, not just the process required to define a problem. Chapter 5 describes an undergraduate course which was created as a result of this research: a course which sought to provide schemes for second-year students to help them understand the key problems in their field and to identify when such problems appeared in realistic case-study scenarios. Finally, Chapter 6 describes the study which was conducted to determine the effect of providing second-year students with these design prototypes. This study found that novices can bring their performance much closer to the level of more experienced students in a problem-definition task as a result of being provided with a Universe of Problems. In fact, according to the sample data, when novices were not presented with a scheme (in terms of a mathematical model) their performance decreased by approximately 9.6%.

Chapter 1 – INTRODUCTION

1.1 The Structure of This Thesis

This thesis is a result of the search for tools capable of helping Industrial Engineers define their design problems well. There was no single obvious place to look for best practices in problem definition for engineers. It was required, then, that research on problem definition was sought from various perspectives. Chapters 1 through 3 form the background for the empirical study placed at the culmination of this dissertation (Chapter 6). Before each chapter is described in detail, a little more will be written about how the stage is set for the study.

Chapters 1 through 3 have very different perspectives, but they are logically related. The perspectives were anthropology, engineering education, and psychology/design. Initially the anthropological approach to engineering education was explored for, what was thought to be, an unrelated reason – interest in understanding engineering culture. The unexpected result of this chapter was that engineering culture was strongly related to the act of (or lack of) problem definition, and specifically, that a solution-focussed culture in engineering has some negative consequences. The literature suggested that a culture defined by problem defining and solving should have positive outcomes.

The discussion of the importance of problem definition from a cultural perspective led to the very logical and practical question of "how." What sort of tools are available to help engineers in their problem-defining activities? Chapter 3 surveys introductory texts in engineering design and papers from Requirements Engineering and summarizes what was found. In general, introductory design texts were thought to be weak in their suggestions and directions for exactly how designers should define the problem or requirements. However, the field of Requirements Engineering was more explicit in describing best practices.

Peer-reviews of Chapter 3 brought valid questions to the surface about the nature of a problem itself. The process for defining a problem is important, but equally so is the goal of that process: what is a problem? And, how can engineers recognize a problem once it has been found? In the end, the key idea that came from this final literature review was chosen for empirical study. This was the Universe of Problems (UOP) approach (see Chapter 4). This method seemed to hold the most promise for aiding students in defining problems. Once the approach was chosen, a new introductory course in IE was structured according to the UOP, and methods of assessment were created to determine if the UOP did indeed help students diagnose problems better. The course is described thoroughly in Chapter 5, and the results of how second-, third-, fourth-, and fifth-year students performed in a diagnosis task are visualized and analysed in Chapter 6. Finally, Chapter 7 outlines key results from all of this work.

1.2 Some Preliminary Chapter Details

Now that the structure of this thesis has been made clearer, the important details of each chapter will be summarized here. Chapter 2 begins with an exploration of the idea of engineering culture, and how culture, somewhat expectedly, has much to do with problem definition. Anthropologists have observed that engineering students do not see themselves as problem definers. Rather, they seem to have great difficulty in working with, and even resist, open-ended realistic engineering problems. Paradoxically, at the same time, the students realize they simultaneously feel unprepared for the "real world." The discussion of culture in this chapter ends with the conclusion that engineering requires a shift where the dominant cultural image moves from engineer as problem solver to engineer as problem definer and problem solver.

Chapter 3 is an exploration of what practical tools are available to help engineers in the problem-definition process. In general, it was found that engineering design textbooks detail very few practical tools to aid students in exploring the structure of a problem. Requirements Engineering, however, has many promising approaches which should help designers focus on the important aspects of their projects (Chapter 4 describes what exactly these important aspects are). The most promising methods for any given scenario depend on the context; however, it is suggested in Chapter 3 that the best methods will often be contextual inquiry, what is called "group" methods, and prototyping. It is important to note that the most effective method with least cost is typically low-fidelity prototyping.

Chapter 4 reviews literature which tries to describe the nature of a problem. It is suggested that a valuable way to structure problems is to define them in terms of Goals, Constraints, Variables, and Strategies (GCVS). The UOP approach to problem identification (also called a scheme-based approach, or Design Prototype approach) is introduced in this chapter and discussed in more detail in Chapter 6. It is purported here that this method will help novices define problems by enabling them to simulate expert behaviour: categorizing design problems in their disciplines.

Chapter 5 describes one such practical execution of a Universe of Problems approach for Industrial Engineering (IE). A new course in IE is described where students are introduced to seven basic models in the discipline: quality control, inventory management, process flow, queuing, human factors, and linear programming. Students are given lectures on the key aspects of each of these models. In addition, they were given laboratory assignments created to focus the students on understanding the basic structure of each model and the effect of any changes in those key features on the system of interest. Initial results suggested that students performed better in a problem-diagnosis task when they were given opportunity to explore the models via lab assignment than when they were given no lab assignment.

Chapter 6 describes a more comprehensive study and statistical analysis of the effect of the scheme-based approach applied as described in Chapter 5. In this chapter, the performance of the second-year students is compared to more experienced students in years three, four, and five. Similar conclusions were drawn from this wider array of data as were drawn from the previous chapter. It was found that, if second-year students were allowed to "play" with the UOP by modelling these problems in Excel, their performance was statistically indistinguishable from the more senior years. However, when second-year students did not complete exploratory modelling, they performed approximately 9.6% worse in their problem-diagnosis task than more senior classes.

Chapter 7 reflects on the work completed in this thesis. This thesis has made several contributions to the literature by: (i) highlighting the importance of and need for problem definition from several angles (anthropology, psychology, design, and engineering education); (ii) bringing to the fore practical tools to be used in the problem-definition stage of the design process, and (iii) empirically testing the concept of the UOP and showing how it can increase performance. This has implications on the practice of instruction in engineering: the problem definition aspect of the design process is very important, there are several tools available for practicing this well, and novices can be helped to exude expert behaviour in the problem definition process by using the UOP approach.

Chapter 2 – ENGINEERING CULTURE AND ITS RELATION TO DEFINING PROBLEMS[1]

2.1 Chapter Summary

The idea for this chapter began with an informal conversation about the issue of gender in engineering. In a conversation with a colleague, we asked one another, "Why is there an issue with regards to gender and diversity in engineering, and what is the cause? Does 'engineering culture' influence how gender and diversity is thought of and reacted to by engineers?" (Lewis, 2017) [2] The content of this chapter is the research that followed this question. In the following sections the concept of culture will be defined in anthropological terms, various conceptions of engineering culture will be explored, and finally what engineering educators can do to improve engineering culture in our contexts will be suggested.

2.2 Defining Culture

Anthropologists study culture, and so the author sought to find, understand, and use their tools to describe the culture of engineering: specifically, that in the undergraduate engineering classroom. Martin defined culture as "ways of acting, thinking, and being in the world" (Martin E., 1998). Although delineating the history of the understanding of culture is far outside the scope of this work, an important development is the significant shift that has been made in the understanding of what culture is in the anthropological community. In the past, anthropologists had thought of cultures as groups of people who share the same beliefs or assumptions about the world (Downey G. L., 2008). Using this definition clarified the differences in the way people lived in different parts of the world; however, it became a hindrance when trying to understand differences within a particular culture. Dividing a world into smaller and smaller subcultures becomes overly complex

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[1] This Chapter is based upon a peer-reviewed conference paper submitted and accepted in 2018: S.A.C. Flemming, C. R. Johnston, and S. MacAulay Thompson, "Becoming aware of Engineering Culture: Toward sculpting a more human engineer," Proceedings of the 2018 Canadian Engineering Education Association (CEEA-ACEG18) Conference, 2018.

[2] Lewis (2017) was the inspiration behind exploring the idea, although there is much literature on gender equality and diversity issues in engineering; for example (de Pillis & de Pillis, 2008; Blosser, 2015; Busch-Vishnaic, Jarosz, 2004; Chubin et al., 2005; Barnes et al., 2017)

and the practice then has limited usefulness in helping ourselves understand one another better when in local contexts (Downey G. L., 2008). Therefore, the “subculture” approach has been abandoned for the idea of defining a culture by its dominant image (Downey G. L., 2008). The idea of the dominant image helps people understand one another in terms of how they respond to the same or different dominant images (Downey G. L., 2008).

2.3 The Idea of Dominant Images

Given that to understand culture one must understand the key images that dominate that culture, what does that mean for engineering? Table 2-1 is a survey of various authors who presented what they believed to be dominant images in engineering. However, many of the writers were not necessary concerned with the “remedy” of the situation so did not explicitly state what an alternative image could be or how one would achieve such an image. Other authors did explicitly share what positive alternative images could be but not precisely how said images might be developed. In these two cases the author noted in the table if there was no explicit image or remedial action proposed and instead described the image and method of remedial action that seemed to be in the spirit of the initial critique.

The papers and books reviewed were almost exclusively written by anthropologists and/or sociologists, historians, and engineering educators or engineers. The author summarized varying dominant images into five images as shown in Table 2-1. The first three images are those posited by anthropologists and sociologists; the fourth is from historians, and the last from engineers.

The anthropological and sociological descriptions are convincing. The papers cited in Table 2-1 give evidence to suggest that the prevailing dominant image in engineering is disproportionately masculine, white, and middle-class. Engineers seem to be technophiles who believe that technology is inherently good, yet they are paradoxically unaware that they are the agents who are tasked with the very difficult job of integrating technology into society. Lastly, engineers are described as problem solvers who think little about for whom they solve problems. This last description overlaps with historians who critique engineers as servants of the dominant class in society. They do solve problems, but they are at the disposal of those with significant power (wealthy leaders of wealthy corporations) and do not have much ability to stop the misuse of, or redirect, that power. The last descriptions are from engineers which paint themselves in a positive light as good practitioners of science who produce useful products for the public good. Although somewhat defensible, this simplistic view of engineering does not address the critical points made by anthropologists and historians.

Table 2-1: Proposed Dominant Images, Alternative Images, and Methods to Achieve Alternative Images

Image Source	Image	Proposed alternative image	Method to achieve new image
Anthropology and sociology	The "macho" technophile middle-class white male with few soft skills "defending" his (sic) profession from "invaders." (de Pillis & de Pillis, 2008; Oldenziel, 1999; Kleif and Faulkner, 2003, Leonardi, 2001; Downey & Lucena, 1997)	Engineers as curious and creative people who turn ideas into reality (Blosser, 2015).	"Clear, consistent, and highly coordinated actions at all levels of management" to recruit and retain more people from marginal populations (de Pillis & de Pillis, 2008).
	Believers that technology in and of itself will solve key social problems (Hnerderson, 1998) (scientists and engineers) as well believers that technology is value-neutral (Escobar et al., 1994; Martin, 1998, Noble, 1977).	Technically adept persons who are aware that their creativity and hard work are required to truly make technology successful (Henderson, 1998) and try and be aware of the social impacts of technology.	*(Not Explicitly Stated)* Self-reflection and self-awareness.
	Engineer as technical problem solver (Downey, 2008, Downey, 2009).	Engineer as problem definer and problem solver (Downey, 2005).	Instructing students on how problems can be defined in multiple ways by multiple stakeholders in engineering core courses (Downey and Lucena, 1997; Downey, 2005) .
History	Engineers as aloof to their role facilitating the dominant classes remaining dominant (Noble, 1977; Yurtseven, 2002) focussed rather on struggling between identity as businessperson or professional Oldenziel, 1999; Layton, 1971).	*(Not Explicitly Stated)* Engineers as those who work for societal good; help society use technology responsibly.	*(Not Explicitly Stated)* Seriously challenge the current political and economic system.
Engineering	Dependable, thorough, consultative, evidence-based, concerned with public safety (Zavrel, 2011) renaissance man (sic) (Yurtseven, 2002).	The renaissance man (sic) (Yurtseven, 2002).	More positive media portrayals of engineers (Yurtseven, 2002).

What do we as engineering educators do in the midst of these valid critiques? The reader would likely agree that all the alternative images in Table 2-1 are positive as well as the method through which to achieve them. Which image(s) and method(s) should we choose to move forward with? The author would argue that, from an engineering-education perspective, one image stands out above the rest: the image of engineer as problem solver. This may be surprising as it seems overly simple; perhaps even simplistic. However, the following paragraphs make the case for using the image of "problem solver" above the other images described in Table 2-1 as an aid in facilitating fruitful change in engineering culture.

The author believes that what is offered by the other images can be encapsulated in the move from "problem solver" to "problem definer and solver." Downey et al. (2009) were responsible for developing ethnographic studies which helped them uncover the image of the problem solver and pursue it in-depth for the purposes of exploring an alternate image that would remedy some of its negative consequences; something none of the other authors were precisely aiming to do[3]. The goal of the scholarship in the study of engineering as "problem solving" and toward "problem solving and definition" was done in order to help achieve almost all the goals as stated in Table 2-1: to change teaching practices so that students would become more politically critical and self-aware (Downey, 2009); to understand perspectives other than one's own and value those perspectives (Downey & Lucena, 2003); and to address the "weeding out" of students from marginal populations by including more in the development of "soft skills" in the core curriculum in addition to the highly technical content (Downey & Lucena, 1997). The next section explores in a more in-depth way the image of the problem solver, how it helps to encompass the various characteristics observed regarding engineers in the above literature, and how moving toward problem definition should help. It is important to note that the method of addressing gender and diversity issues suggested in the first row of Table 2-1 by (de Pillis & de Pillis, 2008) should not be ignored. Universities should make a concerted effort to change the culture with appropriate "top down" approaches

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[3] Downey states that his unique approach "…avoids the comforts of resolute pessimism but risks the dangers of co-optation." (2009) In other words, Downey was not content to create a work only critiquing engineering culture but is also aware that any work that attempts to change the way engineers are educated can be used in such a way that it does not work to change the status quo but only further maintain it. We believe engineering educators must take this risk, since, as engineers we are not in the business of simply tearing down but also building up. One may contrast this with other critical work cited here, for example, that was not focused on beginning remedial action but rather "setting the record straight." (Wajcman, 2000) An important step that must be taken before remedial action can be taken.

(recruitment, policies, etc.). These are crucial strategies that administrators in our engineering schools should be aware of and implement with vigor. However, such strategies are outside of the scope of this chapter. The aim of this section is to provide instructors with the tools necessary to help change engineering culture with teaching practice while our colleagues are working to ameliorate the issue with other strategies.

2.4 The image of "Problem definer" Accounts for Key Cultural Problems

At this point it may serve as a good reminder that, although we could view the above discussion as mainly a summary of unsavoury characteristics of how engineers "act, think, and be" in the world, we are not defining culture as a collection of those actions or beliefs. We think of culture as how a group of people reacts to a dominant image. Rather than asking what may seem to be the more natural questions such as "how might we change various beliefs in the engineering community?" we may wish instead to ask, "what is the dominant image of the engineer and how might it be changed?" As stated above, Downey in many papers has argued the dominant image of an engineer is that of a problem solver (2008, 2009, 2005; Downey & Lucena 1997, 2003). This image is helpful in that it is a single unifying concept that can help us understand where some of the common behaviours seen in engineers and engineering students may have come from. Instead of thinking of engineering students as a group of people who just happen to believe certain things about the world, we can think of the more dynamic interplay between the challenge of and the response to an image that demands the attention of a particular people-group.

The reader may be asking if the image of the problem solver really helps to encompass most of the characteristics described in the literature. Below are various observations from anthropological studies in engineering to illustrate that it indeed does.

Engineers were observed to be consistently and repeatedly over a period of years "programmed" in a machine-like way to follow a strict problem-solving process that will promise tangible results (i.e., the right answer) (Downey and Lucena, 1997). The negative characteristics exuded by engineers described by the authors in Table 2-1 may indeed be ways individuals and groups are coping with the challenge of the image of the engineer. Such an image may be encouraging students to put on a "macho" veneer, to never admit defeat, to defend their work no matter what the cost as described in Leonardi (2001). A pure "problem solver" is one step removed from a machine – could it be that successful engineers have tried so hard to conform to this image that they have become machine-like: anti-social, seeking to minimize communication with others, and apparently preferring the company of technology to humans?[4] (Kleif & Faulkner, 2003; Leonardi, 2001; Martin, 1993)

Being machine-like, one supposes, may have some positives such as efficiency, productivity, and success, but there are human costs associated with these gains. Ethnographic studies expose such costs: engineering students feel the need to make themselves become "invisible" (Downey & Lucena, 1997). Human practitioners feel that in order to be a "good" engineer they must hide the human elements of themselves – especially their feelings (Downey, 2008). They must contort themselves into the shape demanded by the curriculum, have machine-like habits, and consider the rest of one's non-work self as distinct from and subordinate to the "work self" (Downey & Lucena, 1997). Downey, mechanical engineer turned anthropologist, states the conclusion of one study bluntly: "Learning problem solving is precisely about making the bulk of one's identity invisible in one's work" (2008).

The engineering faculty member may be well versed in the idea of a "weed out" course: a difficult course in terms of content and workload that separates those who can succeed in the face of adversity from those who cannot. Downey and Lucena observe that even if students are not "weeded out," part of their humanity is (Downey & Lucena, 1997). Engineers are thought of as round pegs made to be shaped into square holes: their habits must be machine-like: even fun must be had "efficiently" (Downey & Lucena, 2003). Emotions are not valued in the problem-solving process as it is taught now; nor is much else besides studying technical concepts. If one wishes to pursue something else at the same time (e.g. in one study, a student was trying to pursue dancing at the same time), then there comes a point at which the student must choose to pursue one or the other

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[4] Leonardi [7] points out an interesting example of a non-technical engineering book that sought to help engineers navigate the human dimension of engineering by explaining human-to-human interaction in terms of apparently easier-to-understand (perhaps more "logical") actions of computers [20]. In a similar vein Kleif and Faulkner explore the male "love" for technology and surmise that perhaps the dependability, certainty, and predictability of technology attracts the previously mentioned demographic [6].

(Downey & Lucena, 1997). Oldenziel argues women have had to conform to male models of what a professional engineer should be rather than more naturally filling the role in ways that were appropriate given their identities (1999). For example, to be respected as a true engineer, Lillian Gilbreth had to be more qualified, self-reliant, and hard-working than her fellow "Sons of Martha" (Oldenziel, 1999). Similarly, African American students were told by an African American corporate recruiter that they should be careful about appearing "too black" on their resumes; he was suggesting that they should think of themselves as engineers who happen to be black not black engineers (Downey & Lucena, 1997). The contrast of this strict impersonal work versus life identity is stark when compared with other professions such as law or medicine (Downey & Lucena, 1997).

In summary, Downey and Lucena make a claim that the "engineering self" is meant to be the primary identity of a person at the expense of any other identity; they also make the equally pointed claim that it is easier for white males to accept this demand than any other demographic (Downey & Lucena, 1997). They argue that, of any segment of the population, the personal identity of the white male is more likely to overlap with the desires to fix/tinker with mechanical things, seek upward mobility, and minimize the use of emotions in their work life (Downey & Lucena, 1997). So far then, in this paper the author has argued that "unsavoury" aspects of engineering could very well be in large part due to the current dominant image of the engineer – the problem solver. To conclude this section, the author proposes the difficulty with the image of Engineer as Problem Solver is that it forces engineers to divorce their humanity from their work, and favours white middle-class males entering the profession over other groups (Oldenziel, 1999; Downey & Lucena, 1997). Engineering educators may be unwittingly asking their students to become like Charlie Chaplain in "Modern Times" causing the students to feel their humanity being forced to conform perfectly with the modern assembly-line way of life (Chaplin, 2010). How can one be an effective, reliable, consistent, low-variability, and an efficient cog in a corporate wheel unless he or she brings as little of his or her humanity to the world as humanly possible? The author is convinced that this image must change if engineering is to transform into a more wholistic profession that can have a greater positive impact on society. Before a discussion of how engineering educators may influence engineering culture for the better is explored below, the author would like to offer one example of how he has seen the negative effects of the image of "problem solver" in his own experience.

Students in Engineering Economics were given an exam problem detailing the costs and benefits placed before Ford in the 1970s with regards to what to do about the Pinto's exploding gas tank. They were given realistic data that Ford itself was using at the time and asked to decide on a course of action: should they decide to fix the fuel tank at a cost of approximately "x" or decide to simply pay any legal damages at a cost of "y" (with the data resulting in the Net Present Value of "y" being less than "x")? The question was not explicitly labelled an ethics question (although ethics routinely came up in the course) but appeared like the other computationally-heavy questions on the exam. During the next lecture it was revealed to the class that they would lose marks if they decided to produce an inferior product and risk being sued only because it was less expensive. The news was not taken well. Many students were upset and thought it was not fair to ask an ethics question in a technical course. "This is an economics course, not an ethics course!" one student exclaimed angrily. This notwithstanding, the instructor did remind them the night before the exam to review the ethics chapter of the course, and, the Ford Pinto question itself asked what their action should be as a "professional engineer" thus suggesting that they should be thinking in terms of the Engineers Canada code of ethics.[5]

One student spoke to the professor after class and shared her reflection on what had happened: she said that she did not feel that she was allowed to, or that it was appropriate to, choose the ethical option. She felt that she was forced to choose the cheaper option and that the context of the calculation-based exam meant that all other aspects of a question should be "externalized." She had seen that, in other courses, these sorts of details seemed to be unimportant. Our interpretation of this event coincides with the literature: that the dominant image of a true engineer seems to encourage us to make our human selves scarce in order to produce better "results."

This reaction of making oneself invisible is in stark contrast to the Arts and Social Sciences where the individual is prized as a source of knowledge – that if one knows

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[5] Note: when students were shown the crash-test video of the Pinto (available on YouTube), most ceased to argue about losing two points (8%) on their midterm exam.

oneself then one can become a better actor, thinker, or doer in the world. In these academic contexts seeking to become a whole human being is encouraged rather than discouraged (Downey, 2008; Downey & Lucena, 1997). Could engineering benefit from an image that allowed for a more humane and human image of the engineer?

2.5 Sculpting a New Image

Where then do we go from here? How can we imagine new images, and if we do, how can we begin to shape them? What do we want engineers to be – what should they be? Whom should they serve? The Engineers Canada code of ethics states that the ultimate priority for an engineer is to "Hold paramount the safety, health and welfare of the public and the protection of the environment, and promote health and safety within the workplace" (Engineers Canada, 2018). Initially, this image appears superior to that of the "problem solver"; however, there is always the question of "how." How can engineers become leaders of society for societal good instead of corporate employees waiting to be asked to complete tasks (Downey, 2005)? We should ask ourselves the same questions that anthropologists in the area of Engineering Studies ask, "Can engineers be just?" (Schneider, 2010). Can we imagine engineers as critical thinkers who care about who they work for, and to what end? Can we imagine the typical engineer as one who is well versed in, and even enjoys, working with people from various walks of life? Can we imagine engineers as key leaders in municipal, provincial, and federal politics – as highly-trained individuals who know how to understand various points-of-view and can help define and solve large complex socio-technical problems?[6]

Downey et al. suggest the best next step in this "problem" of engineering culture is to begin to replace the image of the engineer as problem solver with the image of engineer as problem solver and definer (Downey, 2005, 2008, 2009). Although a rather simple idea, Downey suggests the practice of entering into the problem-definition space is more complex than it seems, and can significantly disrupt the current image and its negative consequences. With the increase in design courses in the curriculum, we see this

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[6] The Winter 2021 issue of the MIT Technology Review has an article entitled "What I learned from the People who built the Atom Bomb." The author (US Secretary of Defence from 2015-2017) suggests that "technologists" have a key part to play in making sure technology is used wisely and for the good of society [31].

disruption happening, but the students do not know how to cope with it. As an example, consider the students who participated in various ethnographic studies. In these studies, it became evident that the day-in day-out activity of an undergraduate engineering student is almost exclusively solving well-defined technical problems (Downey and Lucena, 1997, 2003). However, engineering students who were in their senior-year design course showed that students typically expressed great resistance in "thinking outside the box" (Downey and Lucena, 2003). It seemed very difficult for them to try and get out of the "just-solve-the-problem" mindset and get into the mindset of a group of people who were faced with an open-ended problem where the exact procedure to solve the problem was not yet known (Downey and Lucena, 2003). The students appeared very uncomfortable in the face of amorphous problems. For perhaps the first time in their four or five years of study they were presented with a complex and real-world issue that was not well-defined and had many stakeholders. The way that the observed students coped was to continually ask authority figures until they were given a clear task. In the absence of this, they would turn a suggestion from an authority figure into a directive and complete those tasks, frustrated that they were not using their technical skills the way they thought they were supposed to (Downey and Lucena, 2003). As an engineer who went through this process myself, these descriptions resonate with the author (and perhaps also the reader) as true-to-life. Is it fair for us to expect much different from undergraduates given they are rewarded again and again over a period of years for following precisely various well-defined methods of solving well-defined problems? Do they feel in their last year of study they are all-of-a-sudden asked to be a different sort of engineer without being adequately prepared?

Downey and his colleagues' response to these observations was to develop an elective course called "Engineering Cultures" where they introduced engineering students to various definitions of an Engineer in different geographic locations and over various periods in history (Downey, 2008; Downey et al., 2006) and lectures can be accessed online. This course, which contained much self-critical reflection, resulted in evidence that suggested students who took the course were able to listen more effectively to people different from themselves and understand better the human dimension of engineering work (Downey, 2006). Downey concludes, however, that he believes the approach of exploring the idea of problem-definition and listening to various perspectives would be far more effective if it were included in most if not all engineering science courses (Downey, 2008) in addition to design courses. He confesses that as an "outsider," his influence is limited, and including such an approach in an elective only serves to further silo the human dimension of engineering from the technical. To truly begin to reshape engineers and the image of an engineer, the technical and human aspects must be acknowledged and practiced in tandem far more often in curricula (Downey, 2008). That being said, with this knowledge passed to us as "insiders" (engineering educators) we now have some tools with which to begin to shape engineering culture ourselves – introducing students to the subjectivity and "art" of problem definition in our technical courses.

2.6 Practical Implications

What then can we do as insiders who care deeply about engineering education? The initial steps to make change in engineering culture are available: to begin to include the more human side of "problem definition" in our courses as much as possible. Although it appears simplistic, the research suggests that adding the task of "problem definition" to engineering science courses can begin to dismantle the image of the pure "problem solver" that brings with it the challenge of creating a culture hostile to persons who are not white middle-class technophile males. The author believes there is convincing evidence to suggest that expanding engineering teaching practice to stress problem definition can result in the production of politically and self-aware engineers, who are able to listen to and understand the perspectives of traditionally marginal voices ((Downey and Lucena, 1997, 2003; Downey, 2009). It is the author's hope that changing the pedagogical approach in this way will lead to a more welcoming environment to the women and other underrepresented groups that currently feel unwelcome in the engineering profession (de Pillis & de Pillis, 2008).

2.7 Conclusions and Forthcoming work

This chapter has sought to provide a framework for understanding the idea of engineering culture and some of the current aspects of the culture that must be changed if engineering is to become a richer and more humane field of study and practice. To move forward, there is much work to be done to understand precisely how curricula can be changed so that engineering students truly are encouraged and allowed to express their human selves and integrate these into their work for their benefit and for the benefit of society.

In the next chapter, this initial literature review will be followed by an exploration of the most effective ways of bringing problem definition into engineering science courses.

Chapter 3 - TOOLS FOR DEFINING THE PROBLEM[7]

3.1 Chapter Summary

In Chapter 2, it was argued that turning attention from the act of problem solving to the act of problem defining has several benefits for engineering students and practitioners alike. Such benefits include developing and refining students' empathy and critical thinking skills inside technical courses. The practical question then becomes how to teach and practise the process of defining the problem well. This chapter is a literature review of the current state of problem definition within engineering design research, and how problem diagnosis can be taught and practiced by engineers. Two significant insights emerge from this review: (1) traditional engineering design textbooks do not practically outline well processes for defining problems; and (2) "Contextual Inquiry" and prototyping appear to be very promising tools for problem diagnosis from an Industrial Engineering perspective.

3.2 Background

Chapter 2 concluded that the prevailing dominant images in engineering culture result in producing engineers who struggle with self- and political awareness, understanding the worldviews of others, and hearing voices from the margins. It was argued that the root cause of these negative traits was that the dominant image of engineering culture is the engineer as Problem Solver (Flemming et al., 2018). The issue is, as one colleague has put it, engineers are taught to be "exercise completers" instead of true solvers of real-world problems (Doré, 2018). An approach to building a greater awareness and understanding of others is to begin to adjust the image of the engineer to be both a problem solver and problem definer (Flemming et al., 2018). As we will see in this companion chapter, defining the problem well also has other benefits: for instance, saving significant resources. We will also see that it is difficult to find processes in traditional engineering design textbooks to aid us in discovering the problem. The author

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[7] This chapter is based upon a peer-reviewed conference paper submitted to and accepted in 2019: S. A. C. Flemming and C. R. Johnston, "The Engineering Design Process - Diagnosing the Problem: "Take Time to Define" with Contextual Inquiry," Proceedings of CEEA 2019 - Learning to Learn - Preparing Tomorrow's Engineers, 2019.

hopes that this chapter will aid the reader in understanding the complexity and challenge in defining problems well, and some of the techniques available to the practitioner.

This chapter will focus on what fruitful methods are available to help designers in formulating problem definitions; however, a reviewer of a past paper (Flemming et al., 2018) asked a key question: what characterises a well-defined problem? This is the subject of the next chapter. In Chapter 4 justification will be given for why a good problem definition consists of describing a system of interest in terms of Goals, Constraints, Variables, and Strategies (GCVS).

The remainder of this chapter will discuss the first step of the engineering design process and how to perform problem definition well. As the reader will notice, almost all the techniques that are described in this paper are in the field of software engineering. This is not intentional; the authors have searched extensively for any literature pertaining to the subject of problem definition and no other discipline was found that engages the subject in such a systematic and practical fashion.

3.3 The Problem Definition Phase

Eleven textbooks were surveyed to better understand the overall design process, but with specific attention paid to the nature and importance of the first step. Each text gave an overview of the engineering design process that typically included some version of the pentagon given in Figure 3-1. Stage 1 was given various names such as: “task clarification” (Pahl et al, 2006), “understanding the problem” (Ullman, 2003), or “establishing the need” (Pidaparti, 2018). In several instances the importance of defining the problem well is stated with great significance. For example, Hurst claims, “…much time, effort, and money can be wasted providing a solution to the wrong problem” (Hurst, 1999). Similarly, Ford and Coulton claim the high cost (in terms of time and financial resources) of re-design makes the problem-definition stage of key importance (2008). Ullman posits that “poor problem definition is a factor in 80% of all time-to-market delays” and tells a story of NASA spending millions of dollars for dampeners on the Mariner IV satellite which in the end were not required (2003). It is the position of the author that such problems are born from designers prematurely skipping from Stage 0 to Stage 2 or Stage 3. The temptation to bypass proper definition and requirements seems to be related to the elements of engineering culture as described above: students and practitioners have the tendency to see themselves as Problem Solvers not as Problem Definers. Engineers seem to feel that they are "wasting time" if they are not immediately getting tangible results. Skipping straight to Stage 3 or Stage 4 (or even Stage 2) can cause significant costs and delays if not done intentionally (e.g. prototyping) to learn more about the problem.

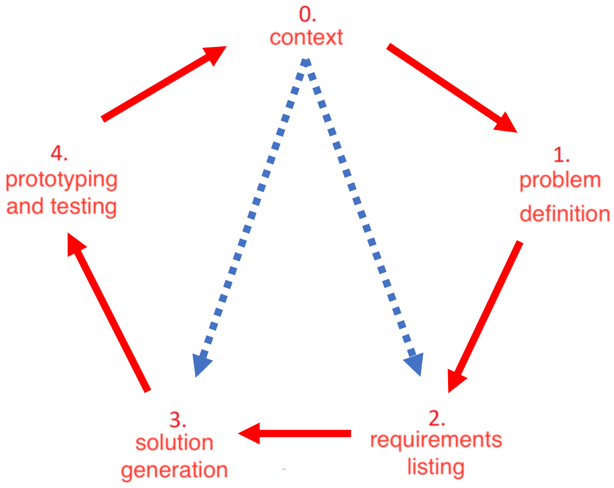

Figure 3-1: The Engineering Design Process

The survey of the textbooks revealed that problem definition is not only important but difficult: the true goals of the client or the project are often not explicitly stated (Pahl et al., 2006; Haik, 2018; Cross, 1994; Eggert, 2005); client problems are rarely crafted in "exam paper precision" (Glegg, 1969), and initial problem statements given by clients can, and often do, "contain errors, show biases, or imply solutions" which needlessly restrict the design space (Dym & Little, 2000). Ullman puts it bluntly: "All design problems are poorly defined" (2003). Complexity further mounts if the design problem includes many stakeholders. Engineering projects in the sustainable development field are an extreme example of the complications that accompany multiple stakeholders with widely varying worldviews and goals. Lucena et al. report that if a project is not defined well in terms of all the relevant stakeholders, then the project will suffer with respect to "ownership, success, and long-term sustainability" (2010). They describe an unsettling example of engineers almost installing toilets for clients who were much better served by the installation of a windmill. See Chapter 6 in (Lucena et al., 2010).

Authors from other (related) fields also describe the ills of defining the problem poorly and the benefits of defining it well (Basadur, 1994). A famous quotation often erroneously attributed to Einstein (in actuality a quote from an Industrial Engineering Department head from Yale) highlights the importance of problem definition: “If I had only one hour to solve a problem, I would spend up to two-thirds of that hour in attempting to define what the problem is” (Finley & Ziobro, 1996). John Dewey emphasizes the same point when he writes, “A question well-put is half-answered; a difficulty clearly apprehended is likely to suggest its own solution,” while also affirming the danger of the opposite scenario: “while a vague and miscellaneous perception of the problem leads to groping and fumbling” (Dewey, 1997). Perhaps John Tukey is pointing out our anxieties to prematurely solve problems when he writes, “Far better an approximate answer to the right question, which is often vague, than an exact answer to the wrong question, which can always be made precise.” (Tukey, 1962). Atman et al. (1999, 2005) confirm these qualitative statements noting that experts spent about 50% more time on problem definition than novices in their study.

Defining the problem is a vital and non-trivial task. To understand the problem better one must, of course, speak to one’s client(s) to learn more about their problems (whether they are consumers in the mass market, or particular clients in a specific consulting project). Here, various authors hint at best practices: approach clients in a collegial and non-combative manner (Dym & Little, 2000), probe until the “real” problem is discovered (Pahl et al, 2006), accept that data gathering will be unsystematic at first since the nature of the problem is not yet certain (Hurst, 1999), and allow one’s views of the problem to shift over time and away from initial solution biases (Dym & Little, 2000).

The reader may be expecting at this point a summary of systematic methods for diagnosing problems. A somewhat baffling result of this literature review is that there is no such summary available from traditional engineering design sources. Although almost every engineering design textbook had something to say about problem definition, most did not have much written about how one was to go about doing it. Consider one design text subtitled “A Systematic Approach.” This particular text had only four of its 617 pages devoted to a discussion on defining problems (Pahl et al, 2006). The fact that there exists so little content regarding the attributes of a good problem definition, or how to go about producing one, gives strong evidence to support the claim that the problem diagnosis phase of the design process is overlooked and underdeveloped in traditional engineering – even though it is clearly considered to be “essential” (McCahan et al., 2015).

What the review of these design textbooks produced so far, then, is an agreement upon which characteristics describe good approaches to defining problems. These characteristics should be considered criteria for evaluating approaches to problem definition that were found from other fields and described in Section 3.4 below. In other words, a “good” approach to defining the problem should: (a) encourage collegiality with one’s client, (b) enable engineers to enter the worldview of their clients and stakeholders, and (c) enable designers to defer or suspend their judgements about what the problem really is until it emerges on its own. A fourth practical concern (d) is that the process should not create an overwhelming workload for designers. These criteria are described in more detail below.

A good approach to defining a problem should (a) encourage a collegial interaction with one’s client. One could argue that any approach to problem diagnosis could be deemed collegial or not depending on the designer and how they use it. To be more precise, an ideal problem-defining tool would be able to develop the skill of collegiality, perhaps even compassion, in the designer. It should be pointed out, that, oftentimes engineers work with a particular and finite number of clients. This means that while some approaches may be meant for learning about many customers as a whole or the “average” customer, this is often not enough for engineering design purposes. In many contexts, engineers must learn about their particular client and customer needs which may be counted in the tens instead of tens of thousands. In these cases, collegiality is all that much more important.

The second requirement for a problem-defining method is that it should (b) enable designers to enter the worldview of the users or customers. Here again, one could argue that many methods of customer discovery or analysis can help a designer understand facts about or data regarding their client. The author suggets, however, that an excellent method would have the ability, if followed well, to open the eyes of the designer so that they may see problems through the eyes of their users – not just understand more about clients in general. Ideally the designer would come to an “aha!” moment realizing that, “Now, I understand why they were having such difficulty!”

Thirdly the authors suggest that a good method of defining a problem would (c) aid the designer in avoiding prematurely diagnosing the problem in their context. The output of the problem-discovery process should be an outline of client experience and the problems with their experience. While such an outline is being created there ought to be recognizable markers for determining when one discovers something of potential value. In addition, to minimize frustration of the designers, there should be an indication as to when the problem definition phase can be ended (at least temporarily). A superior approach will be one that indicates to the designer when “enough is enough” and the next phase of the design process can begin. Lastly, the workload (d) of these various methods is an important criterion as some of the techniques require a significant investment of time and resources.

The next section will be devoted to describing the approaches in the literature that have been created to help designers better understand how to move from Stage 0 to Stage 1 in the design process and resist the temptation to jump to Stage 2 or Stage 3 (see Figure 3-1). In the process of this literature review, it was discovered that the area called “Requirements Engineering” (RE), a sub-discipline of Software Engineering, concerns itself with exactly this part of the design process: defining the problem well in terms of goals, specifications, and constraints (Zave, 1997). It seems to be that eliciting the precise goals and specifications for a software product is particularly important as, if the engineer is not careful, the product delivered can be very different than the product the client expects – much more than in most other fields. Since setting expectations is so important in this field a great host of techniques has been detailed in how one goes about translating client needs and problems into well-defined language. Nuseibeh and Easterbrook have created a very clear and concise categorization scheme for this host of problem-diagnosing (“requirement elicitation” in their parlance) techniques: prototyping, traditional, group, model-driven, cognitive, and contextual (Zave, 1997; Zowghi &

Coulin, 2005; Nuseibeh & Easterbrook, 2000; Goguen & Linde, 1993; Maiden & Rugg, 1996).

3.4 Explanation and Evaluation of Elicitation Techniques

This section is meant to give a high-level view of problem-definition tools for educators and practitioners. Table 3-1 illustrates which of the techniques from software engineering would be most valuable to more traditional engineering disciplines. The authors would like to be clear that they have evaluated the following approaches from the particular context of teaching and practicing engineering design in Industrial Engineering (IE). Each proposed method below then was evaluated from that perspective and according to the four criteria outlined in detail in Section 3.3. Each scheme for problem definition was given a score of unsatisfactory (x), acceptable (~), or very good (✓) with a discussion of those results to follow. If a particular technique is given more than one symbol for how it scores on a criterion, this specifies that "it depends." For example, traditional methods of problem definition have been scored as "x, ~, ✓" with regards to workload as the level of effort depends on how the methods are executed.

Table 3-1 communicates, from an IE perspective, the author believes that Prototyping, Group, and Contextual methods are most promising in aiding the problem definition phase of the design process. A more in-depth analysis follows below.

Table 3-1: Evaluating Methods of Problem Definition

Criterion Method	Collegiality	Worldview	Discovery	Workload	Recommended
Prototyping	~, ✓	~, ✓	~, ✓	✓	✓
Traditional	~	~	~	x, ~, ✓	
Group	✓	✓	✓	x	✓
Model-Dev	✓	✓	✓	x	
Contextual	✓	✓	✓	x,~, ✓	✓
Cognitive	*Not applicable*				

3.4.1 Prototyping

Prototyping normally occurs later in the design process but can be used in this first stage to identify customer needs and issues depending on the context (Zowghi & Coulin, 2005). In this early phase, low fidelity products can be especially useful in helping stakeholders give meaningful feedback and refinements (Zowghi & Coulin, 2005). They are also useful methods of gaining insight into the real nature of the problem and give the users an "active role in developing the [project] requirements" (Zowghi & Coulin, 2005). Prototyping is especially useful if clients are not aware of the kinds of solutions that can exist to solve their problem (Zowghi & Coulin, 2005) or if there is significant uncertainty about what the requirements for the project really are (Nuseibeh & Easterbrook, 2000). A substantial positive of prototypes is that they can be very quickly put together to elicit important feedback from the client. Resourceful designers can sketch out ideas quickly on paper, or even resourcefully bind a few local objects together (e.g. taping together a dry-erase pen, film canister, and clothes pin in a matter of moments (Brown, 2008) to communicate a solution idea to a client.

Prototyping in-and-of itself does not guide the engineer toward collegiality, understanding of client world view, or the art of discovery per-se as much as some of the other methods discussed below. However, on the other hand, when combined with active listening techniques, prototypes can very easily be a pathway into such understandings. For this reason, this technique was evaluated as "it depends" (see Table 3-1). Since prototyping has the ability to very quickly and easily lend itself to collegiality, understanding of client worldview and problem discovery, it is recommended as a good method to aid problem definition.

3.4.2 Traditional Data Gathering Methods

"Traditional" methods of requirements elicitation are those methods of data gathering that are quite familiar to most engineers such as questionnaires, surveys, question-and-answer interviews, analysis of documentation, etc. (Eggert, 2005) which overlap significantly with methods common in commerce (Nuseibeh & Easterbrook, 2000; Blank, 2013). These methods typically focus on quantitative data which can be misleading especially in the early stages of design. With this approach, the customer seems to be more of "a quantity to be measured" (by using surveys, for example) for the sake of developing requirements more than "a partner to be worked with" to diagnose essential problems (Ullman, 2003). In these approaches, much work is done to attempt to understand who the customer is and what they want, but it is done mainly at arm's length through research, literature reviews, and benchmarking (Eggert, 2005; Blank, 2013). While not explicitly anti-collegial, these approaches do not encourage collegiality with the customer and often assume the customer is always a part of some very large consumer group. Architectural Programming assumes a similar posture in learning more about their clients (Peña & Parshall, 2012). These sorts of techniques do take the problem definition stage of their work seriously, and aim to include and understand a multiplicity of stakeholders; but, they seem to devolve into a structured process of simply amassing as much data about as many stakeholders as possible under various categories. While admirable and not adversarial, the author does not believe that these approaches could be described as particularly collegial as defined in Section 3.2.2. These approaches have been evaluated as acceptable (~) since they do describe the importance of getting buy-in from different stakeholders, garnering consensus, and so on but do not give many suggestions concerning how one should proceed in executing those activities (Peña & Parshall, 2012). Similarly, the traditional methods of data gathering do not prevent one from understanding the worldview of the client or discovering something of rich value but seem to fall short in guiding the designer in producing deep insight.

3.4.3 Group Elicitation Techniques

The purpose of group techniques is to facilitate consensus among stakeholders, especially in terms of the key goals (Nuseibeh & Easterbrook, 2000). The title "Group Techniques" casts a wide net: this includes brainstorming and various methodical variations on brainstorming such as Joint Application Development, Requirements Workshops, and Rapid Application Development (Zowghi & Coulin, 2005; Nuseibeh & Easterbrook, 2000, Maiden & Rugg, 1996). These methods have the objective of consensus-building and discovery of the needs/desires of key stakeholders (Zowghi & Coulin, 2005). They differ in that some are more structured than others and some have slightly different purposes. Many, if not all of these, require a greatly skilled facilitator to manage politically challenging situations gracefully and ensure that minority voices are heard (Zowghi & Coulin, 2005). The authors have scored this rather large category as performing well in all the criteria mentioned in Table 3-1. Such tactics, delivered by a skilled facilitator, seem very promising in promoting a collegial interaction, an understanding of worldviews of participants, and a structured approach that guides discovery. The downside mentioned several times in the literature is the human capital required to run such meetings effectively (Zave, 1997; Zowghi & Coulin, 2005; Nuseibeh & Easterbrook, 2000).

3.4.4 Model Development Techniques

Goal-modelling techniques document goals, sub-goals, and various domain entities (Zowghi & Coulin, 2005; Pohl, 2010). They use AND/OR logic and attempt to describe the goals of a system in conceptual models instead of prose (Pohl, 2010). Various specific techniques can be used such as GBRAM, GDC, KAOS, i*, and NFR ; (Zowghi & Coulin, 2005; Pohl, 2010). Such techniques are especially helpful if only the high-level system needs are known, and details of specific issues are not well understood (Zowghi & Coulin, 2005). In another method, the Viewpoints Modelling technique, the designer attempts to view the system from various angles – whether it be from the point of view of various users, or with the goal of seeing how one aspect of the system is affected by all the others (e.g. focussing on the operations or implementation of the system) (Zowghi & Coulin, 2005). There are various particular methods for engaging in a viewpoint analysis such as PREview and CORE one can choose from. The system that PREview uses, for instance, is to name the viewpoint, determine the focus, elaborate the viewpoint's concerns, and list the data source, requirements, and history (Sommerville et al., 1998). There is also guidance in which viewpoints to choose and when to stop collecting data (Sommerville et al., 1998).

These methods are rigorous and have great promise for exposing key requirements for engineering projects and meet the first three criteria well. These methods are, however, very time-intensive and the payback may not be sufficient for the client in traditional engineering design challenges unless the practitioners are entering into a relatively unknown area.

3.4.5 Cognitive Elicitation Techniques

Cognitive techniques, such as laddering (Chun-Hsien & Yan, 2002) were derived from the field of Knowledge Acquisition and can be used for complex knowledge-based systems (Nuseibeh & Easterbrook, 2000). Since these knowledge systems are almost exclusively created and managed in the field of Computer Engineering, we will not discuss them here. The authors believe that such techniques would be of limited use for other engineering disciplines. Some aspects of cognitive techniques that may be helpful (e.g. protocol analysis) can also be considered as belonging to the next group: Contextual Techniques (Nuseibeh & Easterbrook, 2000). Other heuristics such as the "5 whys" are rather simple, and can help in small problems, but are not significant enough on their own to be called an elicitation technique – useful as they may be in some scenarios (Pande et al., 2000).

3.4.6 Contextual Elicitation Techniques

The idea behind Contextual Techniques is to take the stakeholders' tasks, domain, and physical work location into serious consideration when understanding the nature of the client's problem (Nuseibeh & Easterbrook, 2000). Various methods fall under this large umbrella such as: task analysis, domain analysis, ethnography, observation, protocol analysis, and apprenticing (Zowghi & Coulin, 2005). Contextual Design (CD) is one such procedure detailing how designers should observe, interview, and learn from their stakeholders. The goal is to understand the nature of their work very well so that they can design tools to help them be more effective in their work (Holtzblatt & Beyer, 2017).

The contextual (sometimes called ethnographic or ethnomethodological) approaches lend themselves well to fostering collegial interactions with clients. In the Contextual Design method in particular, for instance, engineers are asked to volunteer to conform to the Master-Apprentice model (with their being the Apprentice) when interacting with the client: they are encouraged to always "[t]ake the attitude that nothing any person does is done for no reason" (Holtzblatt & Beyer, 2017). In this method, the engineer-designer is coached to understand that the client has much to offer; and, although the engineer brings crucial technical skills to the team, the client is the expert when it comes to their job and what is required to do it well (Holtzblatt & Beyer, 2017).

Contextual methods also do very well in enabling engineers to enter the world of their clients. Holtzblatt and Beyer, for example, guide their readers in a precise and methodical way how to see through their client's eyes (Holtzblatt & Beyer, 2017). They make a unique and powerful contribution in that they suggest a detailed method of how to do this while also giving engineers the freedom to follow various leads that they deem important given that they are experts in their own discipline.

The CD process helps designers suspend their own judgements on the true nature of the problem by giving a structured process to follow during what they call the "contextual interview." This helps designers set expectations for themselves and the client, understand the purpose of the interview, and to know what to look out for while they are interviewing a particular client (e.g. difficult-to-interpret client actions, emotions, and workarounds) (Holtzblatt & Beyer, 2017). For all the reasons stated above, Contextual Methods have scored very well in terms of the criteria introduced in Section 2. Like many methods, however, the work and resources required can be substantial depending on the scope of the study.

3.5 Summary of Findings

Research was conducted for the purpose of gaining a macro view of what tools are currently available to aid in the problem diagnosis stage of engineering design. Traditional sources in Engineering Design described the positive characteristics of good approaches to problem definition (encouraging a collegial approach, promoting understanding of the worldview of the client, and enabling discovery) but did not describe how to execute problem definition well. When other sources were sought, especially those in the area of Requirements Engineering (RE), several methods of how to perform problem definition were outlined in great detail. Given the author's experience consulting and teaching in Industrial Engineering, the most appropriate methods of problem diagnosis were deemed to be Prototyping, Group, and Contextual. Which should be used in a given situation will depend on available time, human, and financial resources.

If time is a significant constraint, prototyping would be the best method for a more quickly gathering a sense of most important aspect of a problem. If more time is allowed, the Contextual Interviewing process is recommended. This takes increased time but can be done within a reasonable timeframe with adequate results and with less use of human capital. Finally, if resources are not in tight supply, either more elaborate contextual interviews or group elicitation techniques can be undertaken to aid in the problem-definition process.

3.6 Next Steps

This chapter has explored best practices in defining a problem well especially when considering how to conduct primary research with clients. The next chapter will explore what the product of this process should be: i.e. how one can describe a well-defined problem. It will also include a discussion of how experts and novices differ in their approach to defining problems and what sorts of educational interventions might be the most fruitful in helping novices adopt expert behaviours related to effective problem definition.

Chapter 4 - THE NATURE OF A PROBLEM, SCHEMAS, DESIGN PROTOTYPES, AND AIDING THE PERFORMANCE OF NOVICE DESIGNERS[8]

4.1 Chapter Summary

The previous chapters have exposed the importance of problem definition practices in engineering design. This chapter seeks to determine what is the basic structure of a problem, and if an educational intervention related to this key structure may help novice designers. This chapter shows that scheme-based instruction ameliorates novice performance in well-defined tasks in the pure sciences but also in ill-defined contexts such as medical diagnostics. For this reason, the authors argue that scheme-based instruction will also be effective in supporting design tasks. Conclusions from the below are twofold: (i) a problem can be described well if it is characterized in terms of its Goals, Constraints, Variables, and Strategies (GCVS); and (ii) engineering educators should present their students with schemes that categorize the key problems in their fields in terms of GCVS. These schemes, or "design prototypes," show great promise in helping novices mimic an expert breadth-first strategy in defining their design problems.

4.2 Problem Diagnosis: An underdeveloped aspect of Engineering Design

The fields of artificial intelligence and cognitive psychology have spent much time on this question of the nature of a problem with fruitful results. This chapter details those results and how they may apply to engineering design: i) problem construction may be the most important cognitive activity in creative problem solving, ii) problems can be described in terms of four key elements (GCVS), iii) experts outperform novices in the task of problem construction, iv) expert pattern recognition can be replicated to a significant degree in novices if they are provided with "schemes" to diagnose common problems, and v) research in engineering design largely agrees with these conclusions

Problem diagnosis is a valuable, but often neglected, part of the creative problem-solving process. There are both institutional and personal barriers to doing this well, not

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[8] This chapter has been submitted to a journal and is currently under review. An earlier version of this chapter was included in conference proceedings in 2020: S. A. C. Flemming and C. R. Johnston, "The Nature of a Problem, Problem Diagnosis, and Engineering Design," in Proceedings of the 2020 Canadian Engineering Education Association (CEEA-ACEG20) Conference, Montreal, 2020.

least of these are cognitive biases which can encourage individuals to ignore concerns in favour of business-as-usual, re-label issues as someone else's problem, not problems at all (Basadur, 1994), or simply disregard them as irrational complaints (Klein & Weitzenfeld, 1978).

Temptations aside, real problems require acknowledgement and appropriate structure to their context if they are to be solved well according to their stakeholders. The engineering profession demands that engineers seek to do work that is for the betterment of society and the environment, especially when inconvenient (Engineers Canada, 2020). In can also be said, somewhat crassly, that solving real ("workplace") problems is what engineers are paid to do (Jonassen et al., 2006), so they have a responsibility to do it, and educators have a responsibility to prepare them. Einstein writes on the matter, "The formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old problems from a new angle, requires creative imagination and marks real advance in science." (as quoted in Getzels and Csikszentmihalyi (1975)). Engineers must do the hard work of defining the problem very well to make real gains and advancements for the "wicked" problems they often face.

There is evidence to suggest, however, that engineering educators are not enabling students to understand the structure of real-world problems (Hoover & Feldhusen, 1994). Engineering students graduate with the feeling that they don't know how to "do" engineering (Hutchins, 2015); after many years of solving textbook exercises students are lost and even resist complying when finally given a realistic design problem to engage with (Downey & Lucena, 2003). They have been habituated to the process that years of textbook exercises have taught them to expect: "Given, Find, Equations, Diagram, Solution" (Downey, 2008). Although automaticity in skill execution is a necessary part of becoming an expert, it is not sufficient (Hardin, 2003). The authors argue that to complete design tasks well, novices must also understand their problems conceptually and execute effective domain-specific strategies (Hardin, 2003; Ball et al., 2004; Daugherty & Mentzer, 2008). A word of caution comes from Downey (2005) who suggests that if engineering educators do not soon begin to teach our students to think more critically about the work that they do, the profession will lose the privilege it currently has. If business-as-usual continues, it is possible that engineering will be reduced to something like IT where problems will be defined in "exam-paper precision" and reduced to technical tasks for engineers to simply carry out (Glegg, 1969). Educators must develop methods of problem diagnosis that engage students in critical thinking to avoid such a future where engineers are essentially cut out of the decision-making process and their socio-technical knowledge is left untapped.

In contrast, studies have shown that persons who invest significant time in problem construction tend to excel in their careers, be better recognized, and produce better results in a wide array of areas such as art, science, and political science (Reiter-Palmon & Robinson, 2009). A metanalysis suggests that problem construction is the most valuable of all cognitive processes that have to do with creativity (Reiter-Palmon, 2017). It would not be a stretch to claim this also for creative problem solving: several authors suggest that there is no creativity without problem solving (Getzels & Csikszentmihalyi, 1975; Mumford et al, 1994). Although it is an uphill battle to war against the obscure nature of problem definition, human biases, inertia, and student resistance, engineering educators must give students the tools they need to define their problems well so that they are solving the right ones for the right reasons.

4.3 Ill-Defined Contexts Require Definition

Often educators use the word "problem" to describe both simple textbook exercises and complex design challenges (Woods, 2000). However, in the literature, these two scenarios are often appropriately placed on opposite ends of a spectrum that ranges from "well-defined" to "ill-defined" problems.

Well-defined problems are those in which the need or issue is easy to identify (Klein & Weitzenfeld, 1978). That is to say: the goals, constraints, specifications, and actions required to achieve the goal state are so easily described (Holyoak, 1984; Schwenk, 1983) that a solution is practically executed before a second thought is given to the problem (Reiter-Palmon & Robinson, 2009). Current, desired, and intermediate states can be reasonably easily represented, and the quality of those states can be practically measured (Holyoak, 1984). By contrast, ill-defined (or "wicked," "unstructured," "workplace," or "strategic") problems are sometimes called "messes" since they are the opposite of well-defined problems (Jonassen, 2000). Stakeholder/client goals are often mistaken, vague, incomplete, and lack clarity (Klein & Weitzenfeld, 1978); supporting information provided or found regarding the system of interest is often confusing (Jonassen, 2000). Even if there are few or even just one stakeholder, "messy" problems have conflicting values and goals (Jonassen, 2000).

Various researchers describe a problem continuum: Basadur reports that problems can be defined as ill-structured, semi-structured, or well-structured (Basadur, 1994). Mumford cites a study that defined these three categories more precisely as (1) wholly presented exercises, (2) questions where all information is provided, but require some work in discovering the proper elements from within the information provided, and (3) problems that need to be almost entirely structured by the problem solver (Mumford et al., 1994). Getzels and Csikszentmihalyi use binary variables in a particular way to create various degrees of presented versus needing-to-be discovered problems (1975). They have defined their problem spaces to be functions of whether the problem, method, or solution is known or unknown (Getzels & Csikszentmihalyi, 1975). Similarly, Reid and Yang (2002) quoted an introductory chemistry textbook that described the eight-category problem space as a function of the data, methods, and goals being well-defined or not.

As one reads an overview of the sorts of problems that engineers encounter, the question becomes how one goes about structuring ill-structured problems so that they become more like well-structured problems. This is the express purpose of problem construction. "Problem construction is concerned with defining the goals, objectives, and parameters of a problem-solving effort" (Mumford et al., 1994). The purpose of this activity is to transform vague situations into better specified problem models (Schwenk, 1983). In other words, the goal of problem construction is to make explicit the context for problem-solving efforts so that system states and relationships amongst key variables can be better predicted (Mumford et al., 1994; Schwenk, 1983). This is the role of engineering educators teaching design: to enable students to transform ill-defined problems into well-defined problems.

4.4 The Nature of a Problem

Various authors over the years have sought to describe the elements of a problem. Jonassen (2000) claims that a problem is simply an unknown entity that has some cultural value. He suggests, at this very high level, problem elements are structuredness, complexity, and domain-specificity (Jonassen, 2000). Newell and Simon (1971) focussed on well-defined problems and suggested that problem elements depend on the task instructions (especially with novices) and previous experience with similar problems where "programs" from long-term memory are recalled to produce a solution. The same authors (1972) describe a problem as initial state(s) of knowledge about a particular task, goal state(s) of knowledge about the task, and operators (information processes) which transform the states. Others have followed suit with very similar definitions (Klein & Weitzenfeld, 1978) in stating that a problem is some sort of need that can be described in terms of current state, end goal state, and transition states. Still others propose that a problem should be described in terms of constraints, available resources, transformations, and processes (Jonassen, 2000). The somewhat vague term, "operators," (Holyoak, 1984) can be translated as "solution plans and procedures" (Klein & Weitzenfeld, 1978; Newell & Simon, 1972). Over the years then there has been a wide variety of suggestions as to how to a problem ought to be defined.

Of all the literature surveyed, Holyoak (1984) has the most precise and yet exhaustive definition of a problem. He writes that focus should only be placed upon "causally relevant" elements in a context in order to define a problem well. System models should only include elements which influence the structure of the system and not simply surface characteristics (Holyoak, 1984). He writes that an "ideal problem model is one that describes all the elements of the world that are necessary and sufficient for concrete realization of a successful solution plan." (Holyoak, 1984) His identification of key problem elements has not been modified from its inception into problem-finding literature until now (Reiter-Palmon, 2017; Reiter-Palmon & Robinson, 2009). The specific elements and their descriptions are:

- Goals (the desired state(s) at some level or various levels of abstraction)
- Constraints (limitations to action, such as available resources, etc.)

- Variables and information (note that variables could be “soft” such as stakeholders. “Information” seems to refer to data required for accurate and reasonable assignments of values to said variables).
- Actions and operations intended for transforming system state (sometimes also referred to as strategies (Hardin, 2003), procedures (Newell & Simon, 1972), or trajectories (Wickens et al., 2013)

Therefore, as engineers approach an ill-defined problem, they should seek to define the system goals, constraints, variables, the information needed to approximate variable values, and state transformation strategies. Describing these aspects of a problem exposes critical elements of the system structure, cues engineers to similar problems they have encountered in the past, and thus affords help in shaping the next steps in the engineering design process.

4.5 Cueing Pattern Recognition: Design Prototypes

Experts outperform novices in diagnosing problems due to expert schemata. Schemata are organized and diverse cognitive structures which allow an individual to more easily recognize and identify relevant problems especially in complex, novel, or poorly-defined contexts (Mumford et al., 1994; Schwenk, 1983). They can better identify the important causal features of a situation which help categorize the type of problem as well as the features that are critical in order to achieve the solution (Schwenk, 1983). In contrast, novices typically focus on the wrong problem elements which are only “surface” or of little consequence with regards to attaining the goal state (Schwenk, 1983). “Schemes” are explicit conceptual problem representations based on experts’ implicit mental schemata (Hardin, 2003; Gick & Holyoak, 1983; Shoenfeld, 1980; Marshall, 1995). Schemes help stimulate chunking behavior in novices (Hardin, 2003; Gick & Holyoak, 1983). Very little has been written about schema-based instruction in the engineering realm (engineering sciences or design), but interventions have been successful in physics, math, and other sciences (Hoover & Feldhusen, 1994; Schoenfeld, 1980; Streveler et al., 2008). Based on these results from other scientific fields, we expect scheme-based instruction to garner positive results in engineering design.

This being said, engineering design is not simply another scientific context to apply scheme-based instruction: the studies mentioned above have been in the context of well-defined mathematical or scientific exercises. Since we are interested in effective instructional techniques to give structure to open-ended design problems, the closest analogy thus far discovered is research in medical education. It is argued here that diagnosing the correct disease in medical science is quite like problem definition in engineering design. Like medicine, engineering design seeks to identify and solve the most problematic issues in complex real-world systems. As in medicine, there are several competing and conflicting goals, data accessibility issues, data quality challenges, and multiple important stakeholders.

Early medical education was developed under the assumption that the practice of the scientific method was essentially the same as the practice of clinical diagnosis (Groen & Patel, 1985). It was assumed that the hypothetico-deductive (i.e., guess-and-test) scientific method used to generate medical knowledge was also the best method to utilize in medical practice: diagnosing diseases in patients (Groen & Patel, 1985). However, when told to use a hypothetico-deductive approach novices and experts alike performed very poorly in a diagnostic task (Mandin et al., 1997). Conversely, when experts used "pattern recognition" (a function of experience so this method was not available to novices) they were ten times more likely to diagnose an illness correctly (Mandin et al., 1997). When asked to use a scheme-based approach, both novices and experts were five times more likely to provide a correct diagnosis (Mandin et al., 1997). In related research, Beck noted that how medical educational materials were organized for teaching purposes made a significant difference in the ability of students to diagnose illnesses in patients (Beck & Bergman, 1986). When information was presented and categorized with respect to pathophysiology (aspects of cyanotic and acyanotic heart disease) as opposed to categorized in terms of symptom presentation (diagnostic cues), students were much less likely to diagnose typical as well as atypical cases of the diseases properly (Beck & Bergman, 1986). In other words, scheme-based instruction works in ill-defined complex systems. Although the conclusion sounds somewhat obvious (of course if one teaches diagnosis then students will diagnose better), medical educators were not teaching diagnostic schemes to students to help them learn how to diagnose well. We argue, that right now, the same could be said about engineering educators: we are not presenting our teaching materials to facilitate design; rather we are teaching students encyclopedic knowledge in engineering science (Hutchins, 2015; Downey & Lucena, 2003; Downey, 2008; Downey, 2005; Redish & Smith, 2008). Scheme-based instruction will work in the ill-defined context that is engineering design. The next section will detail some explicit, and many implicit, references to the idea of using schemes to help novices in their design work.

4.6 Related Work in Teaching Design and Engineering Education

The above works were mainly from cognitive psychology, with some work in artificial intelligence and medical science. In this section we follow the topic from the perspective of researchers who study design and engineering education who seek to understand the differences between novice and expert design behaviour.

Most researchers make, often implicitly, the assumption that experts are better designers and so their behaviours and practices should be (for the most part) adopted by novices. Much work has been done in this area to contrast experts and novices in this way. Ahmed and Atman report that experts gather more information than novices and do so more confidently (Ahmed et al., 2003; Atman et al, 1999). They transition much more often between steps in the design process (Atman et al, 1999; Cross, 2004), budget their time well to ensure they are able to get to the end of the design process, and tend not to get stuck or fixate on a step (Cross, 2004).

In addition to these basic, perhaps easy-to-label behaviours, there are those that are more complex. Experts are said to have, in general, a different design approach and typically include a "preliminary evaluation" of their ideas before they delve deeply into them (Ahmed et al., 2003), which some may call breadth-first instead of depth-first, or, since experts do not follow this rule strictly, it can be called a "balanced" approach (Cross, 2004). In a similar vein, some call the approach of expert designers, in general, a more "systematic approach" (Cross, 2004). Experts seem to have a knack for what is variously called problem finding, problem reframing, (Ahmed et al., 2003; Cross, 2004) or scoping (Cross, 2004). Framing, which effectively means forcing their understanding of the problem on a context, helps experts by setting the stage for the next few "moves" (we could call these “strategies,” using the language from Section 3.4) in the design process (Schon, as quoted in (Cross, 2004)). Some researchers simply notice that there are elements of expert design behaviour not present in novices that can only be called “intuitive” (Ahmed et al., 2003; Worsley & Blikstein, 2016). This intuition may be related to, or a function of, their use of higher levels of abstraction (Marques, 2017) or their use of classification schemes. Gero (1990) pinpoints the key ability of experts highlighted above: the use of schemes to guide their thought. He talks about schemes in general, but in the context of engineering design, refers to these schemes as “design prototypes” (Gero, 1990). That is, experts have a compendium of basic design problems in their mind, and, when they see a new situation that appears to fit one of those categories, they retrieve one of these design prototypes and begin to work with it (Gero, 1990). This is very much related to problem framing mentioned just above. Experts choose a design prototype to help frame the context and use this to suggest strategies for completing the next few steps in the process.

In contrast to these expert tactics, the literature finds that novices approach the design process in ways that are not always helpful. Ahmed et al. (Ahmed et al., 2003) describe the novice approach to design as lacking strategy altogether: their “strategy” seems to be just a series of thoughts and actions, basically a “guess-and-test” method of design. This finding mirrors what was reported above from the medical domain: novices attempt to diagnose patients with a very ineffective and inefficient guess-and-test method that mimics the scientific method. They have trouble seeing patterns and connections within and between their context and their education (Reid & Yang, 2002). Novices tend to summarize and repeat what they have seen others do and neither seek nor find deep comprehensive relations within their problems of interest (Chang & Kuwata, 2020). They tend to be distracted by surface features and details of a problem (Chang & Kuwata, 2020). Novices jump to solutions pre-maturely, do not question data they are given (Chang & Kuwata, 2020), and fixate on solutions developed very early in the design process (Cross, 2004). They do not spend enough time scoping the problem from a big-picture perspective (Atman et al., 1999) but, instead, perform depth-first analyses of the solutions upon which they have fixated (Cross, 2004). Novices desperately need help in connecting various “islands” of data and ideas (Reid & Yang, 2002) to help make up for their lack of experience. The author hypothesizes that novices will be better able to detect patterns and use a breadth-first approach in problem definition if they are provided with expert schemas (design prototypes) and opportunities to explore those design prototypes.

Providing students with opportunities to explore expert design prototypes is one answer to the questions posed in the literature, "Are there educational interventions we can design that will help novices behave more like experts?" (Atman et al., 1999; Cross, 2004). Although these questions have been posed clearly for some time, most of the research in this area, so far, has been dedicated to the understanding of the differences between novice and expert behaviour as stated above. In 2012, Douglas et al. noted the same theme: many strategies are suggested but few are based on research evidence. For example, Chang and Kuwata (20200 have written a very thorough literature review of the differences and suggest that various interventions should help novice designers: cognitive apprenticeships, encouraging novices to organize their own schemas, visualizing their problem definition (see the note on Romer regarding sketching the problem space below), and finally transitioning from learning about design to being a better designer. As the wording suggests, these ideas (what seem to be very good ideas indeed) have not yet been tested and appear to be based on those authors' own significant design experience. Allam et al. (2012) implemented many interventions, mainly in the form of project management aides, but did not measure differences between groups receiving these interventions and those not. Likewise, Marques (2017) has planned to create a study to test how teaching the Ideation Framework to novices improves their design ability but has not yet published a paper on the matter.

Recently, however, there have been more studies which have attempted to test particular interventions to see if they have a positive effect on design outcomes. Romer, in her study (2000), finds the simple and intuitive practice of sketching the problem space improves the efficacy of problem analysis. Schimph et al. (2019) found that their AI tools which generated alternate designs helped their human counterparts explore ideas and designs they likely would not have thought of otherwise. Ozaltin et al. (2015) noted that increased iteration in early design phases and much iteration in the marketing phase impacted novelty of designs to a significant degree. (This study, however, does not report on if the design solutions were more impactful, useful, efficacious etc., only their novelty). Hughes and Denson (2021) found that teaching their "SCOPE" process accounted for 40% of the variability of design scores in junior high and high school students. Various authors have explored the idea of "Model Eliciting Activities" (MEA) which encourage students to take a real-world problem and attempt to describe models which help them solve said problems (Diefes-Dux, et al., 2004). They have found that use of MEAs has shown to benefit students' ability to problem solve and understand key engineering concepts (Shuman et al., 2012). They have also been shown to increases the attainment of professional skills, as well as self-efficacy and metacognition have also been reported (Besterfield-Sacre et al., 2012).

The previous two sections illustrate that pattern recognition is a key aspect of expert behaviour in design. Therefore, one would expect that well-designed educational supports which facilitate pattern recognition in novices would increase novice performance levels in a design task. It is suggested here that a valid form for such an intervention would be: (i) lecturing students on design prototypes using the GCVS framework (largely based on Holyoak's (1984) summary), and (ii) providing students with numerical examples of basic design prototypes for them to explore to gain experience in understanding key relationships within and between these prototypical examples.

4.7 Creating Design Prototypes for Engineering Design: A Basis-Set of Problems

In the preceding pages the authors have argued for the need of scheme-based instruction in engineering design. If this premise is accepted, the next step is to begin to create a "universe" of design prototypes for our students (Marshall, 1995). Once Mandin (1997) saw the strength of the effect of organizing teaching material in terms of diagnostics instead of pathophysiology, he called for a "new taxonomy of medical problems" so that the "comprehensive knowledge domain" could be more appropriately structured for knowledge acquisition and usage. The author posits that in our profession a new taxonomy should also be developed, and it would appear that Gero (1990) would also make such a claim. This kind of reorganization of our educational materials will better facilitate what Mumford et al. (1994) call “systematic screening” of problem representations in their desire to find the best and most creative solutions to real problems. In the case of engineering design, the schemes presented would be intended to help students recognize problems in terms of their deep structures and approach the design process with an expert-like breadth-first strategy (Cross, 2004). These design prototypes will be composed of key goals, constraints, variables, and strategies for particularly important and common problems in a given engineering domain (Ball et al., 2004; Daugherty & Mentzer, 2008). The next step, then, is for engineering educators to find design prototypes for their particular area to help their student engineers recognize the symptoms of an “ill” system. The authors have chosen to do just this in the discipline of Industrial Engineering (IE) and have completed such design prototypes, also known as the “Universe of Problems” (UOP), as part of a new course launched to improve the IE curriculum. The next chapter details the development of this course and preliminary findings regarding the use of design prototypes. The final chapter of this thesis details a study which hypothesized that student engagement in numerical prototype models may increase novices performance in completing a problem-definition task.

4.8 Summary

Research suggests the problem definition stage of the design process has the greatest impact on creative and successful solutions. In the medical field, novices diagnosed ill patients as effectively as experts when they were given relevant schemes to use in order to find appropriate patterns in an ill patient. It is argued here that engineering students will perform better in problem-diagnosis tasks if they are provided with design prototypes (a Universe of Problems) from their discipline which describe typical design problems in terms of goals, constraints, variables, and strategies. Although no such study has yet been performed, other researchers such as Gero (1990) intimate that supporting the development of such design prototypes in novices should encourage expert behaviour. The next chapter describes a Universe of Problems for IE, and the final chapter details a study that tests the effectiveness of these design prototypes.

Chapter 5 - DEVELOPING PATTERN RECOGNITION THROUGH MODEL CREATION[9]

5.1 Chapter Summary

This chapter describes an introductory course in Industrial Engineering (IE) which was created to increase students' ability to appropriately use fundamental IE models and increase their conceptual understanding of these models. The models introduced are the following: quality control, inventory management, process flow, queuing, human factors, and linear programming. Only the most elementary models in each category are presented, allowing students to spend more time on basic concepts, inherent assumptions, and interpreting results in a valid manner. Students use Microsoft Excel to create and modify their models. Students are also given a method to determine which model(s) may be appropriate for a particular scenario; that is, to identify the goals, constraints, variables, and strategies (GCVS) for the context and compare these to typical GCVS for a particular problem category. Student success in the problem diagnosis case studies was used as an indicator of conceptual understanding and pattern recognition ability. Initial analysis of assignment data suggests that pattern recognition ability increases when students engage in contextualized numerical modelling tasks.

5.2 The Need for "Introduction to Modelling in IE"

The "Introduction to Modelling in IE" course was created to give second-year undergraduate students exposure to the discipline of Industrial Engineering and experience creating and modifying systems models. The authors and other faculty members have noticed over time that students in their graduating year seem to have difficulty in, (1) understanding concepts behind basic models in IE, and (2) choosing which model is appropriate to apply to a given real-life scenario. This course was created with the intent of helping to rectify these issues.

The content of this course builds upon the practical implications of significant literature reviews written in the first three chapters of this thesis (Flemming et al., 2018;

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[9] A version of this chapter was provisionally accepted to "Operations Research Forum" in September 2021 and is due to be published in early 2022.

Flemming et al., 2019; Flemming et al. 2020). In the last chapter it was suggested that the next step was to develop "design prototypes" to help students recognize typical problems in their field (Flemming et al., 2020). Akin to diagnosing an illness in a patient, these schemes are meant to help novice engineers see which is the most pressing need in a system of interest. The author would like students to be able to tell if an organization is suffering from, for example, a quality control, inventory, or queuing (etc.) "disease."

5.3 The Strategy to Meet Learning Goals: The Act of Modelling

To respond to the goals of aiding students' conceptual understanding and application of fundamental IE models, the lab assignments for this course had the following characteristics:

Open Ended and Flexible: Students were given freedom (to some degree) regarding which tools they chose to use, how they decided to use them, and how the results were interpreted. The sections below detail, for example, how students themselves decided on which values of the Order Quantity (Q) they would explore when developing an inventory policy, which diagrams they felt were most useful in analysing a production environment, which graphs could be best used to describe variability in a production process, and which avenues (prototypes) to pursue when trying to improve the design of an interface. This open-ended approach was meant to encourage students to see modelling as a tool for developing interpretations and conclusions, not as a method for finding the right answer.

Requiring Translation from Reality to Abstract Model and Back Again. Students were given realistic (typically simulated) data for their assignments. This was done with the intention of requiring them to think about, and respond to, the fact that data is typically found in a different form than is required by a model. Examples of this are shown below where "holes" (or N/A values) in the Quality Control assignment were purposely given to students. For the Queuing assignment raw arrival times, service start times, and service end times were given to students so they would have to calculate inter-arrival times and service durations. For the Linear Programming assignment, students were asked to estimate lower and upper bounds for their models without being able to compare these to calculated optima. Incidentally, some students seemed very disoriented when they were asked to estimate realistic answers without having learned how to find the optimal answer first. Others had difficulty understanding the difference between a feasible answer and the process required to find the optimal answer (e.g., the simplex method). These sorts of student reactions illustrate just how important these realistic exercises are.

5.4 Choosing Design Prototypes in Industrial Engineering

The author chose the following as design prototypes in the field of IE for the purposes of this course: quality control, inventory management, process flow, queuing, human factors, and operations research. As suggested by Marshall (1995), this "universe of problems" was chosen by looking through common IE curricula, typical models used in final-year design projects at our particular university, and introductory textbooks on the matter such as (Shtub & Cohen, 2016; Turner et al., 1992; Atkins, 2019). First, the past two years of capstone projects were analysed for problem themes. Once the themes were elicited, they were compared to the IE curricula and introductory textbooks. There was significant overlap in these three items, and the seven categories were chosen as listed above.

The author does acknowledge that this is not an exhaustive list of all relevant models in the discipline, but believe it is a helpful starting point for undergraduates beginning their career in industrial engineering (or depending on your institution these models could be considered foundational in management science, systems engineering, and so on). This universe of problems will undoubtedly be supplemented and refined over the semesters to come. It is hoped that future research will explore systematic methods for helping to determine better and more categories.

The following subsections will describe the design prototypes in detail, the lab assignments meant to facilitate exploration of said models, and some potential lab solutions (since these were open-ended there could be several acceptable submissions that would garner full grades).

5.5 The Idea of a "Problem" Versus a "Model"

As mentioned above, Chapters 2 and 3 have explored the importance of defining a design problem well and also what exactly constitutes a problem. These literature reviews found that a problem can be defined in terms of goals, constraints, variables, and strategies (GCVS). One could also posit that models can be defined in a similar way. Models exist to help us achieve certain goals by manipulating variables (through various strategies) while abiding by certain constraints. Although contrasting problems and models will be the subject of a future paper on its own, it is argued for the time being that the difference between a model and a problem is mainly in terms of which strategies are available to the modeller.

For this course, students were engaging with models, not problems. They were given a hypothetical assignment, and their strategies for finishing the exercise and reaching tentative conclusions were restricted to statements of assumptions, manipulation of variables that result in solutions and ranges of solutions. However, with regards to problems, engineers have more macro-level strategies available to them: going to the physical system of interest to gather more raw data, buying new software, sub-contracting the work, interviewing stakeholders, deferring the issue until a later date, and so on. For the purposes of these assignments the instructor expected students to use different methods of data manipulation, calculation, and visualization to better understand the system of interest and draw conclusions about its behaviour. (Note: For this reason, for the remainder of this chapter, the subject matter of the technical lab assignments will be considered models, and the subject matter of the qualitative case studies will be considered problems.)

5.6 Using a Modelling Environment to Engage Critical Thinking

The reader is reminded that the purpose of these assignments was to push students to understand, create, and explore important models in IE through modelling the system of interest in Excel. The course was designed so that the students would not see their technical work as their final product but rather as a tool for understanding and drawing conclusions about a system of interest. Each assignment that will be discussed below was created to reduce the temptation for students to merely mimic or replicate what they have seen in class but rather engage in critical thinking about their task at hand. Critical thinking was demanded by the instructor by marking student understanding of model assumptions, interpretations of their results, and ability to make convincing arguments to suggest why their interpretation of the data was valid. Of course, technical correctness was also a key aspect of the grading process.

The problems detailed below, in their focusing on realistic scenarios, are similar to Modelling Eliciting Activities which were created to develop conceptual and profession skills in engineering students (e.g. Diefes-Dux et al., 2004). However, the MEAs, unlike the problems below, did not focus on particular categories of problems. As Yildirim et al. (2010) report, the creators of the MEAs were more interested in crafting problems that abided by six principles: model construction, reality, self-assessment, model documentation, generalizability, effective prototype. These problems were the vehicle with which those authors wished to elicit positive learning outcomes such as professional skills (Besterfield-Sacre et al., 2012). The goal of this thesis is different: the author is concerned here with familiarizing students with particularly important problems in their field in such a way that they become more adept in diagnosing those problems when they see them elsewhere.

5.6.1 The Quality Control Model

For the quality control assignment (please see Appendix 1), students were given simulated ambulance response times, dates, and order in which the incidents took place. They were given directions regarding which tools may be useful to complete the assignment (stem and leaf plot, histograms, time-series plots, and so on) and asked to justify why they thought the process may be in or out of control. They were also given a link to a recent news article so that they would understand the current struggles and debate about ambulance response times. The article describes background concerns and how extremely long delays have almost resulted in deaths in the city. Also included in the piece is the government-mandated target response time. The instructor made a point of not explicitly repeating this goal for the students (8 minutes and 59 seconds) but instead directed related questions back to the article.

Instructor solutions are shown below in Figures 5-1 to 5-3. Students created similar visuals and, for the most part, did behave as expected by interpreting the graphs in a common-sense fashion suggesting the process was out of control for two basic reasons: (1) most (over 90%) of the data points are above the goal response time of 9 minutes; and (2) there is a trend of the response time increasing as a function of calendar date. The lion's share of students showed that they were able to use the tools available to them and appropriately draw conclusions.

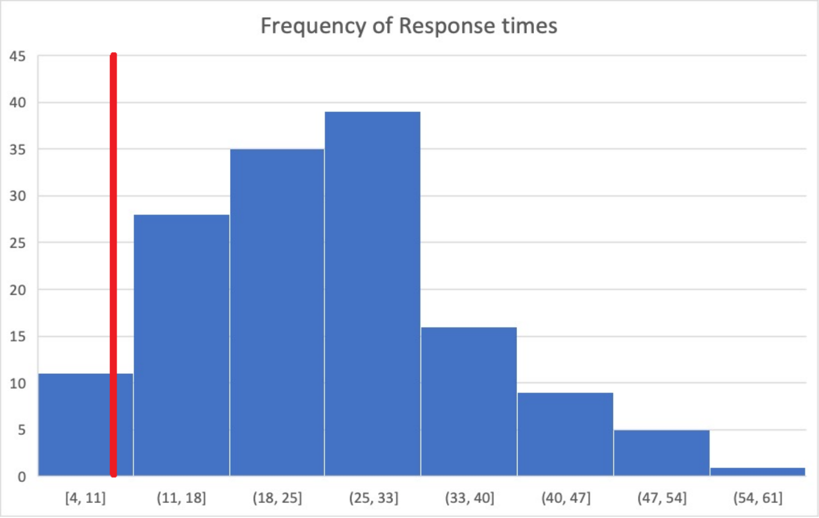


Figure 5-1: Distribution of Simulated Response Times. This Shows that Less Than 10% of the Data Meets the Desired Nine-Minute Goal.

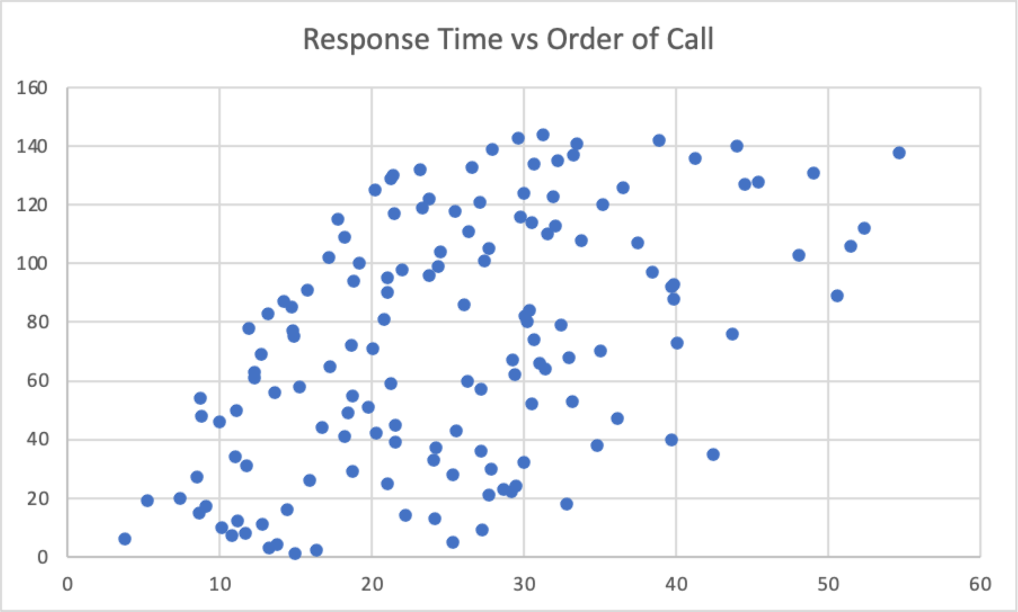


Figure 5-2: In General, this Simulated Data Set Shows that Response Time Increases as Incident Number Increases.

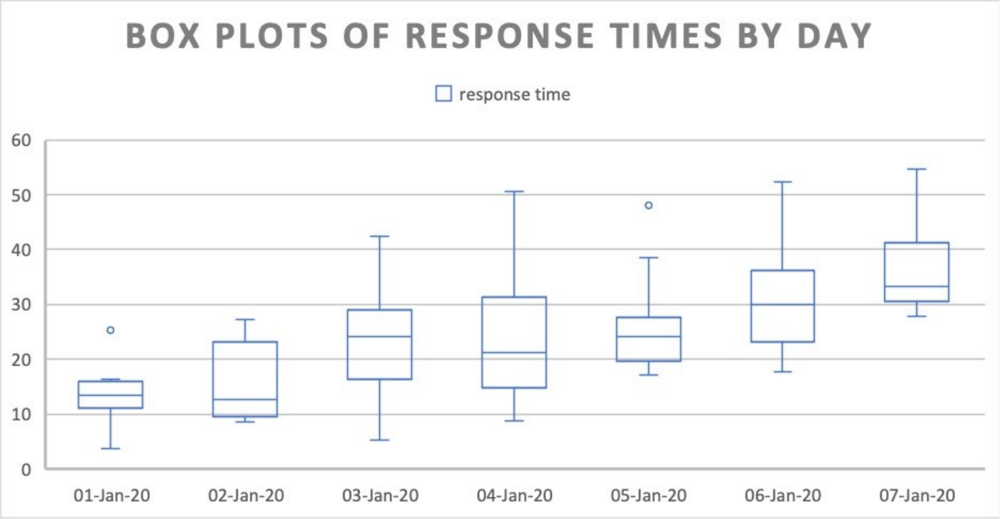
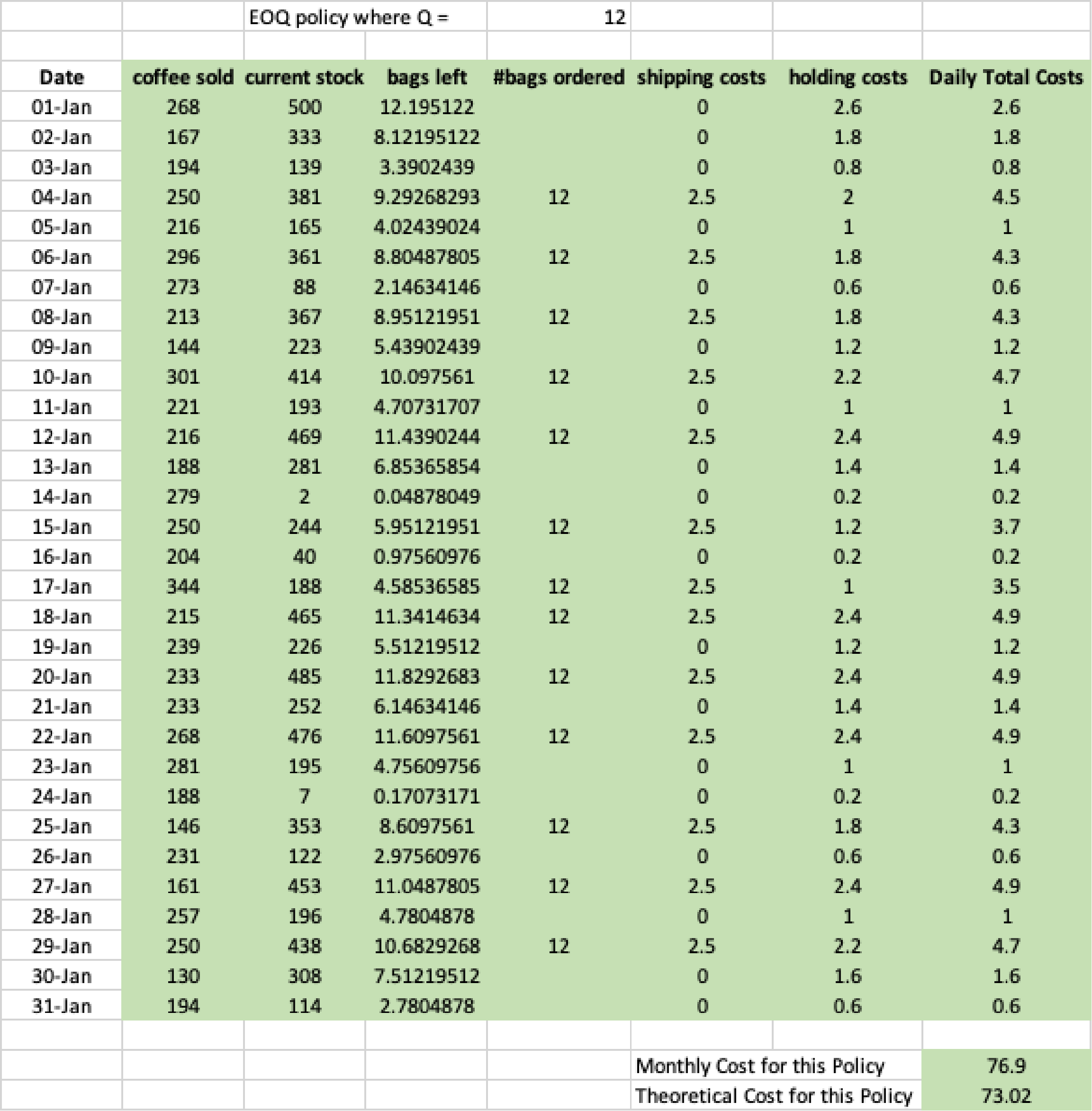


Figure 5-3: Over Time We See that the Boxplots Migrate Higher and Fewer Data Points Meet the Nine-Minute Standard (Courtesy of Dr. Zhuojun Liu).

5.6.2 The Inventory Management Model

Students were introduced to the Inventory Management model in lecture and lab and then given a practical numerical case study to analyse and interpret (see Appendix 2). In this assignment, they were given simulated forecast data on the expected number of coffees to be bought each day for the next month at a local coffee shop. They were asked to help their client (the owner of the shop) determine what to do in order to lower their overall inventory costs.

Table 5-1: Practical Implementation of an Order Policy



		EOQ policy where Q =		12			
Date	**coffee sold**	**current stock**	**bags left**	**#bags ordered**	**shipping costs**	**holding costs**	**Daily Total Costs**
01-Jan	268	500	12.195122		0	2.6	2.6
02-Jan	167	333	8.12195122		0	1.8	1.8
03-Jan	194	139	3.3902439		0	0.8	0.8
04-Jan	250	381	9.29268293	12	2.5	2	4.5
05-Jan	216	165	4.02439024		0	1	1
06-Jan	296	361	8.80487805	12	2.5	1.8	4.3
07-Jan	273	88	2.14634146		0	0.6	0.6
08-Jan	213	367	8.95121951	12	2.5	1.8	4.3
09-Jan	144	223	5.43902439		0	1.2	1.2
10-Jan	301	414	10.097561	12	2.5	2.2	4.7
11-Jan	221	193	4.70731707		0	1	1
12-Jan	216	469	11.4390244	12	2.5	2.4	4.9
13-Jan	188	281	6.85365854		0	1.4	1.4
14-Jan	279	2	0.04878049		0	0.2	0.2
15-Jan	250	244	5.95121951	12	2.5	1.2	3.7
16-Jan	204	40	0.97560976		0	0.2	0.2
17-Jan	344	188	4.58536585	12	2.5	1	3.5
18-Jan	215	465	11.3414634	12	2.5	2.4	4.9
19-Jan	239	226	5.51219512		0	1.2	1.2
20-Jan	233	485	11.8292683	12	2.5	2.4	4.9
21-Jan	233	252	6.14634146		0	1.4	1.4
22-Jan	268	476	11.6097561	12	2.5	2.4	4.9
23-Jan	281	195	4.75609756		0	1	1
24-Jan	188	7	0.17073171		0	0.2	0.2
25-Jan	146	353	8.6097561	12	2.5	1.8	4.3
26-Jan	231	122	2.97560976		0	0.6	0.6
27-Jan	161	453	11.0487805	12	2.5	2.4	4.9
28-Jan	257	196	4.7804878		0	1	1
29-Jan	250	438	10.6829268	12	2.5	2.2	4.7
30-Jan	130	308	7.51219512		0	1.6	1.6
31-Jan	194	114	2.7804878		0	0.6	0.6
					Monthly Cost for this Policy		76.9
					Theoretical Cost for this Policy		73.02

Students were asked to experiment with different order sizes as well as determine the Economic Order Quantity (EOQ). They produced tables like Table 5-1 for at least four order sizes (Q) of their choosing. They then were asked to produce a graph like Figure 5-4 to illustrate the bathtub-type curve that is expected when attempting to balance holding and ordering costs. Students were also asked to comment on why the tabular total cost was different than the total cost calculated by formula, and to contextualize their best solution for the client. Full marks were given to those who realized that the table captured more accurately the variability in demand whereas the formulas only consider the average demand. A few also commented on the fact that the theoretical EOQ value could sometimes be beat by a different value due to this fluctuation (in my case, Q = 15 resulted in a lower total cost than the EOQ of 12). Students were also asked to elaborate on the solution in terms a client could understand. That is, instead of simply stating "EOQ = 12" as their final answer, they were expected to be able to explain to the client that they should be keeping track of inventory, and when they do not have enough inventory to get them through the expected lead time of the delivery, they should order the proposed ideal quantity (around 12-15 units).

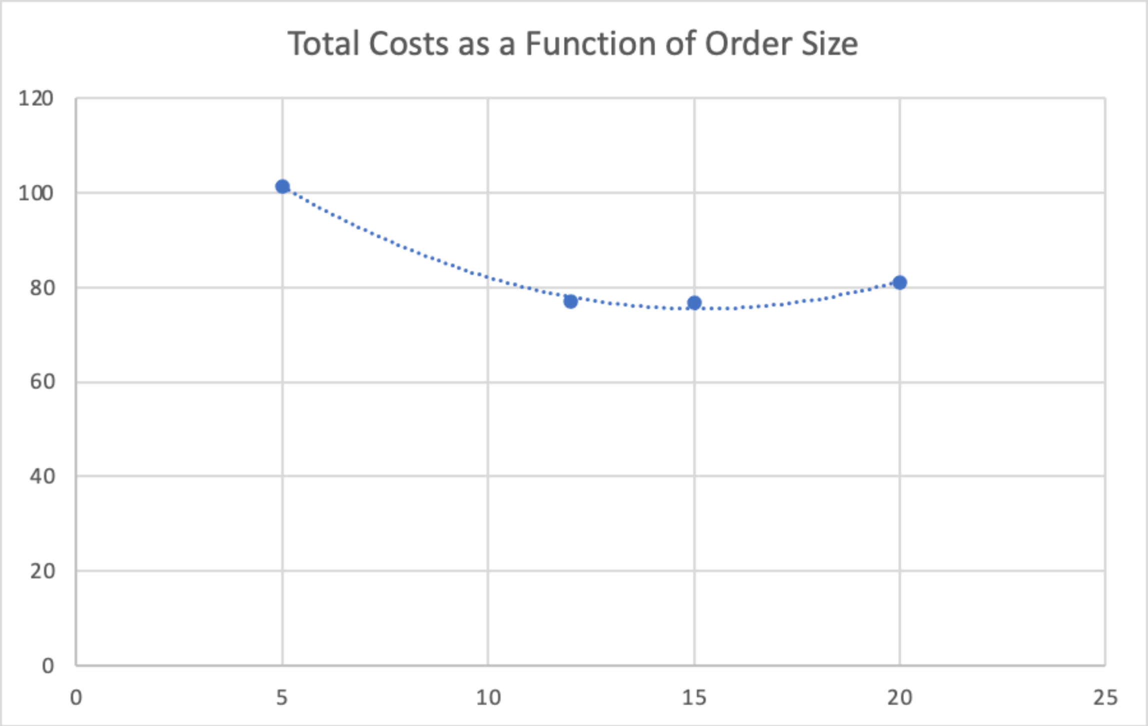


Figure 5-4 - Total Cost as a Function of Order Size (Q)

5.6.3 The Process Flow Model

The process flow model is so fundamental to IE that it is often overlooked as a model at all. However, depicting how work flows through a given system, as simple as it may be, is often the first valuable step in analysing any system of interest. For this assignment students were given a link to a video of a real production process and asked to use tools to model the system, estimate its production, and suggest improvements that could be made to the production process (see Appendix 3).

Below, the work process and work environment is translated into these two very simple models: the Operation Process Chart (OPC – see Figure 5-5) and the Flow Diagram (Figure 5-6). The OPC shows the steps of the process, any task precedence requirements, and the associated approximate task times. This was created to highlight the time, precedence, and when new materials were added, but did not reflect the layout or number of operators at each station. The Flow Diagram shown in Figure 5-6, however, does model the physical layout of the assembly process and could be modified to include the number of operators, location of inventory, and so on. Students were also given the option to use other tools they may have been familiar with if they desired.

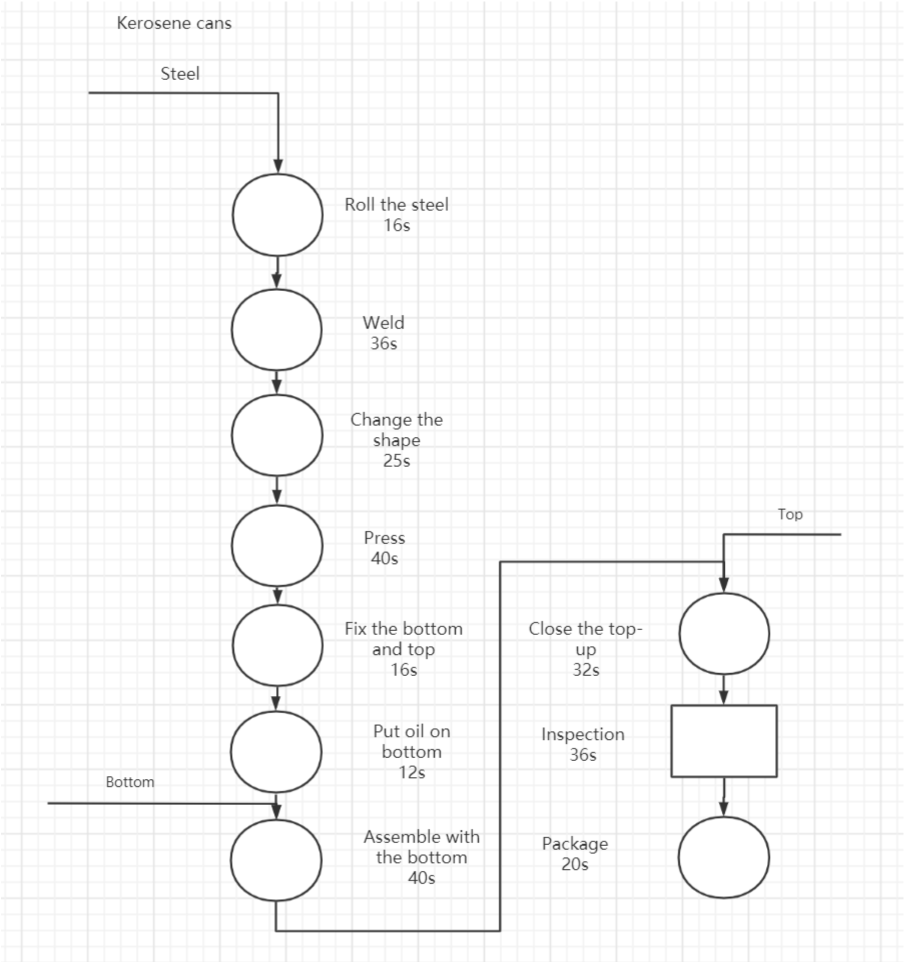


Figure 5-5: Operation Process Chart for the Kerosene Can Production Process (courtesy of Dr. Zhuojun Liu)

Undergraduates were asked to use their models of the system to suggest improvements. The most salient improvement was to balance the assembly line. Many students noticed that the workload during the video was not balanced with the four workers having tasks that ranged in duration from 16 to 145 seconds. Typically, students also reported that there was a lack of safety gear available or being worn; very few noted that raw-material and other inventory did not seem to be placed conveniently.

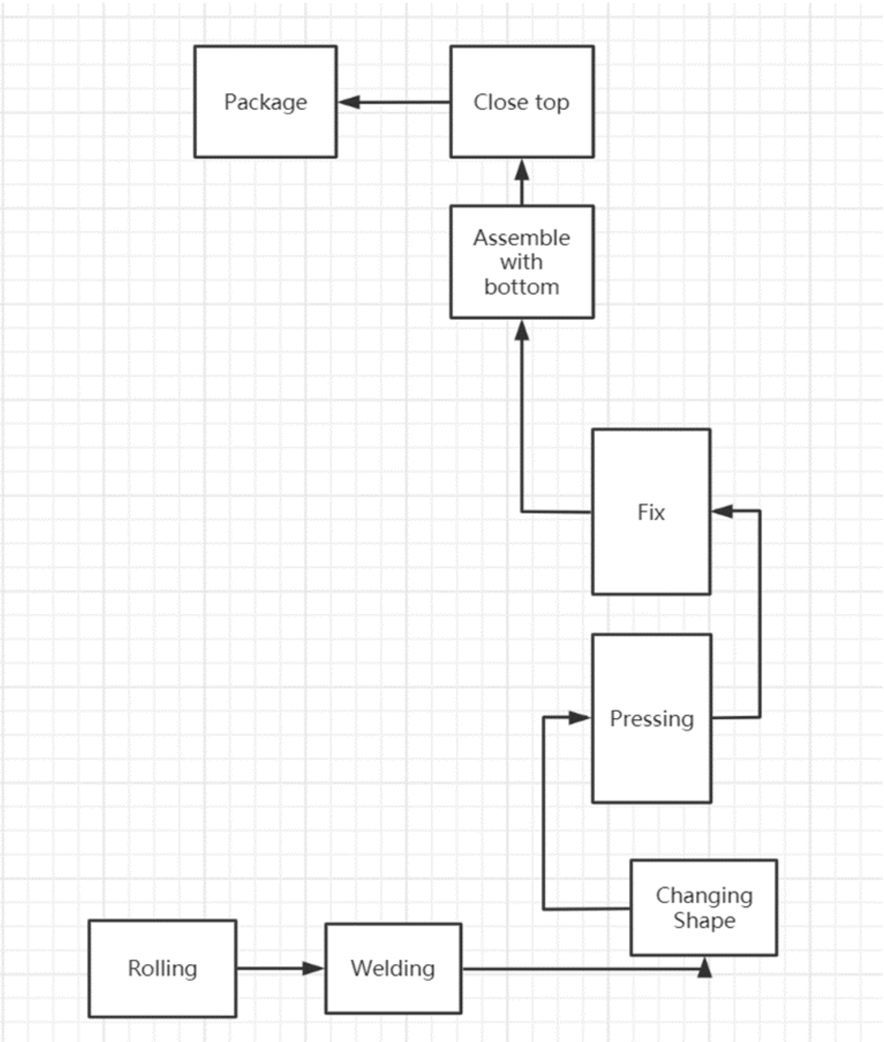
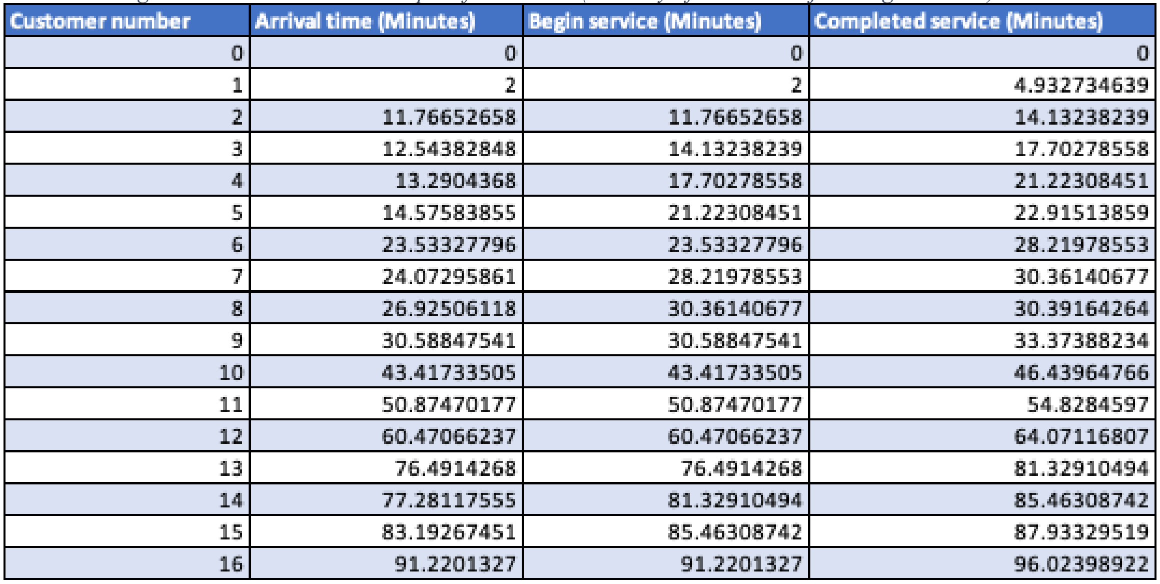


Figure 5-6: Flow Diagram for the Kerosene Can Production Process (courtesy of Dr. Zhuojun Liu)

5.6.4 The Queuing Problem

For the Queuing Problem students were given simulated data on commercial airplane arrival times, service start and end times, and some service requirements (lines not to exceed a certain length and a target wait time). With these data and requirements students were asked to determine if the system was indeed meeting the required standards and to justify why or why not. To do this formulaically, they would have to translate the raw arrival times and service beginning and end times (see Table 5-2 and Appendix 4) to inter-arrival times and service times.

Table 5-2: Flight Arrival and Service: Sample of Raw Data (courtesy of Mr. Simranjeet Singh Chadha)



Customer number	Arrival time (Minutes)	Begin service (Minutes)	Completed service (Minutes)
0	0	0	0
1	2	2	4.932734639
2	11.76652658	11.76652658	14.13238239
3	12.54382848	14.13238239	17.70278558
4	13.2904368	17.70278558	21.22308451
5	14.57583855	21.22308451	22.91513859
6	23.53327796	23.53327796	28.21978553
7	24.07295861	28.21978553	30.36140677
8	26.92506118	30.36140677	30.39164264
9	30.58847541	30.58847541	33.37388234
10	43.41733505	43.41733505	46.43964766
11	50.87470177	50.87470177	54.8284597
12	60.47066237	60.47066237	64.07116807
13	76.4914268	76.4914268	81.32910494
14	77.28117555	81.32910494	85.46308742
15	83.19267451	85.46308742	87.93329519
16	91.2201327	91.2201327	96.02398922

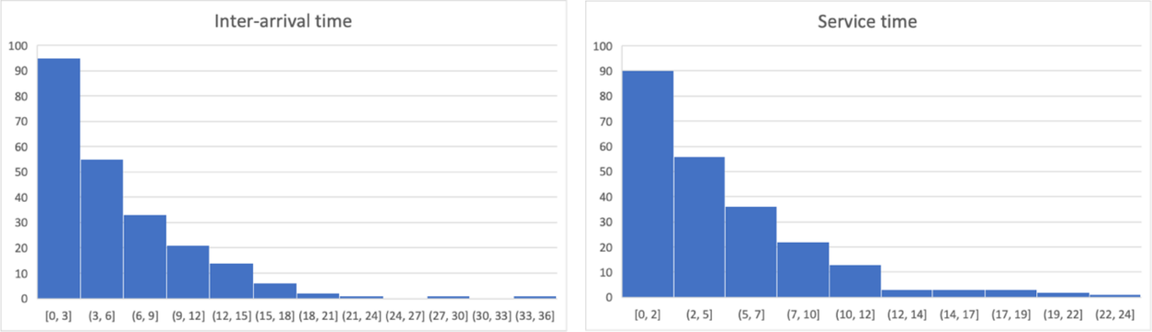
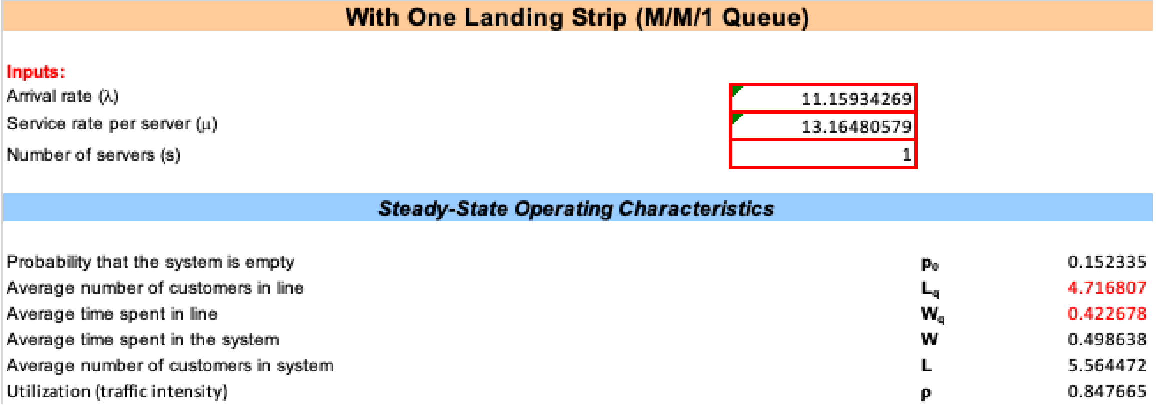


Figure 5-7: Histogram Used to Help Determine if Exponential Arrival and Service Times are a Reasonable Assumption (courtesy of Mr. Simranjeet Singh Chadha)

Students were also responsible for verifying model assumptions. A minimum expectation was that students would plot histograms such as those shown in Figure 5-7 before they attempted to use Little's Laws. The histograms indicate that assuming inter-arrival and service times adhere to an exponential distribution is reasonable. The instructor solution then used Little's Laws to understand various system characteristics (Table 5-3). The model illustrates that the length of queue and wait times are both violated if only one landing strip is available. With two landing strips, however, both requirements are met (see Table 5-4). The length of the queue (Lq) is, on average, less than 1.75 planes and the average time spent in line is less than four minutes (note that the Wq values in these tables were calculated in hours). Students should have come up with similar approaches and also concluded that a second strip would be necessary to meet the required targets.

Table 5-3: Analysis of Current State: Queue Performance with One Landing Strip (courtesy of Mr. Simranjeet Singh Chadha)



With One Landing Strip (M/M/1 Queue)

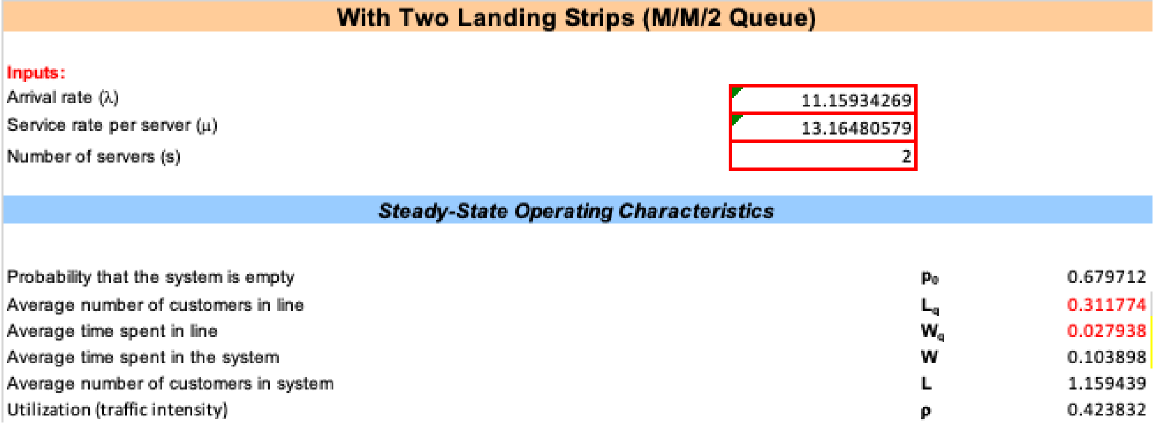
Inputs:

Arrival rate (λ)	11.15934269
Service rate per server (μ)	13.16480579
Number of servers (s)	1

Steady-State Operating Characteristics

Probability that the system is empty	P_0	0.152335
Average number of customers in line	L_q	4.716807
Average time spent in line	W_q	0.422678
Average time spent in the system	W	0.498638
Average number of customers in system	L	5.564472
Utilization (traffic intensity)	ρ	0.847665

Table 5-4: System Performance of Potential Future State: Two Landing Strips (courtesy of Mr. Simranjeet Singh Chadha)



With Two Landing Strips (M/M/2 Queue)

Inputs:

Arrival rate (λ)	11.15934269
Service rate per server (μ)	13.16480579
Number of servers (s)	2

Steady-State Operating Characteristics

Probability that the system is empty	P_0	0.679712
Average number of customers in line	L_q	0.311774
Average time spent in line	W_q	0.027938
Average time spent in the system	W	0.103898
Average number of customers in system	L	1.159439
Utilization (traffic intensity)	ρ	0.423832

5.6.5 The Human Factors Problem

Human Factors engineering (HFE) is a very large field and representing the area with only one model could be seen as unfair to the discipline. However, it is believed that some exposure is better than no exposure, and students were informed that this small assignment only acted as a very brief introduction to the field. A goal of this course was for students to critically engage an interface of some kind (in this case a website or app) and be able to suggest improvements from an HFE perspective. For this assignment, the model of interest is the human-machine model which highlights that machines must be designed with the human (the intended user) in mind in order to truly be effective. Failure to consider the human is a failure in engineering design.

For this particular assignment a checklist based upon Wickens et al.'s Introduction to Human Factors Engineering (2017) was used (labelled as table 15.1 in their text) in order to help students critique a website or app and suggest improvements. The instructor used a checklist similar to the one shown in Table 5-5 to provide an example of evaluating an online form (note that the actual table provided by Wickens et al. (2017) could not be reproduced here for copyright reasons).

Table 5-5: Usability Checklist to Assess a Website or App

Usability Guidelines for Assessing a User Interface				
	Bad	**Neutral**	**Good**	**Comments/Suggestions**
Is the User's Short-Term Memory Helped?				
1				
2				
3			🟩	
4				
Can the Interface be Easily Controlled?				
1	🟥			
2				
3				
Is the Current Status of the System Obvious?				
1		🟨		Could give steps completed so far
2			🟩	
3			🟩	
4	🟥			Could give total # of steps in process
5			🟩	
Is the Interface Consistent?				
1			🟩	
2			🟩	
3			🟩	
Does the interface map to the real-world well?				
1			🟩	
2			🟩	This online form was intuitive
3			🟩	(similar to filling it out on paper)
4			🟩	
Can Errors be Mitigated Well?				
1	🟥			Should catch errors earlier
2		🟨		(in phone #, email, post code)
3	🟥			Should give error messages
4	🟥			Should tell how to fix the error

A few human factors design principles were found to be violated in the interface analysed by the instructor. Basic sketches on how, for example, errors could be reduced and highlighted with the inputting of email addresses are shown in Figure 5-8. The students were asked to do the same sort of analysis and prototyping in their assignment with websites and apps of their choosing (see Appendix 5) and justify their suggested improvements with the best practices noted in the readings.

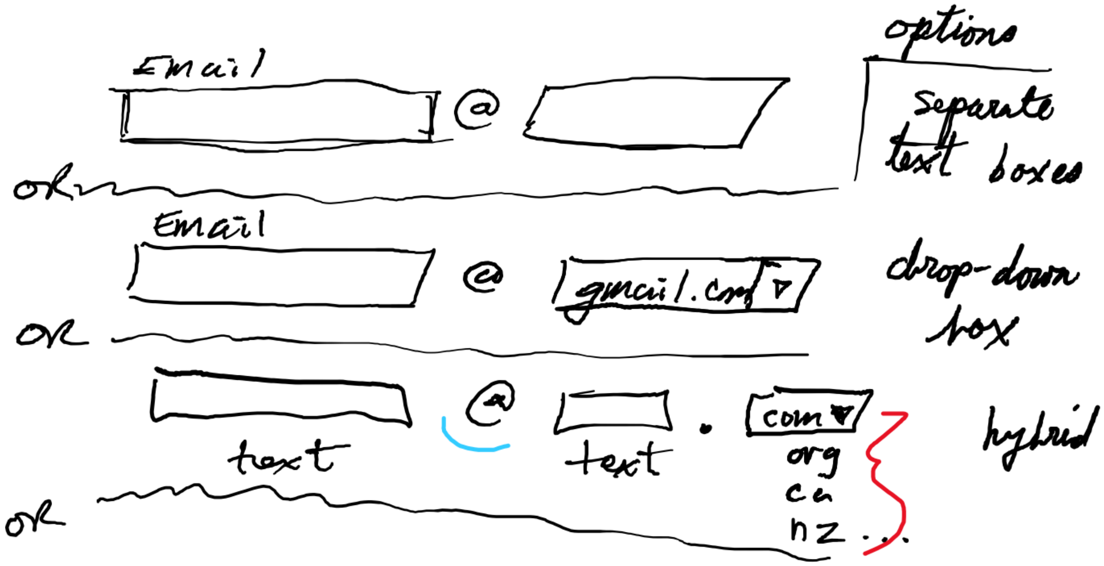


Figure 5-8: An Example of Rudimentary Prototypes Designed to Improve Error Detection on an Online Form

5.6.6 The Linear Programming Problem

The linear programming (LP) aspect of this course is fundamental to our undergraduate program. The introduction to LPs in this course is meant to prepare them for core courses such as Operations Research 1 and Operations Research 2 but also for further core and elective courses (Project Management, Facilities Design, and so on). For these reasons the authors wanted to make sure that important concepts were well understood. The approach for this section was different than the five previously described sections due to the importance of the topic but also for two other reasons. First, if all students are given the same model parameters in their assignments (as was the case here) formulation of LPs have little room for variation. Second, solving LP models is much more complex than the previous topics – whether it be analytically or with the aid of computer software. Since those technical approaches will be covered in depth by subsequent course work, the instructor wanted to focus on the practice of formulating the model as well as estimating reasonable solutions to the model (see Appendix 6 for more details).

The sorts of problems that can be modelled by LPs are enormous so the instructor felt it was important also to share a macro view of what categories of problems can be modelled well with Linear Programming. Hillier (2015) suggests three basic categories: resource allocation problems, cost-benefit trade-off problems, and network problems. Ideally, we would show an example of each of these three categories here, but, one example (a network problem) should suffice in demonstrating the approach the instructor took to teaching the LP modelling section in general. See the example below:

"A senior manager in an engineering consulting firm has to choose which projects to give to which Professional Engineers. She has put together some historical data on how each person available has done (on average) in the past with similar projects. She wants to assign personnel to do the best overall job but isn't sure how to maximize the result.

		Employee Performance (In Terms of Return on Investment (%))				
		Karissa	Amy	Abdul	Carl	Talah
Project Type	Construction	36.6	31.8	32.2	35.6	32.4
	Manufacturing	42.4	31.1	41.1	32.7	40.8
	Management	30.3	25.5	32.9	22.4	31.4
	Research	27.6	24.1	25.2	22.5	29.0

Right now, one of each category of job must begin in the next two weeks. How should our manager assign the projects to their currently unoccupied staff to achieve the best return on investment for the firm?

- Formulate this problem as an OR linear model (but do not solve it).
- Find a simple way of getting an estimate for the best possible set of assignments (your solution does not have to be valid)
- Find a simple way of getting an estimate of the worst possible set of assignments (again, your estimate does not necessarily have to be valid)
- Find a solution for this problem that you think will perform well but will also be a valid solution
- Compare your solution with the best and worst estimates – how does it perform?"

The reader will, in all likelihood, be able to solve this assignment problem in a matter of minutes. The novelty in this modelling exercise is not solving the LP, but the estimations mentioned in the second and third bullet points above. Here, the instructor intended for students to have practice engaging with the model and making sense of it before they learn how to solve the problem at a future time through the Hungarian Algorithm or some other technical process. Acceptable methods of finding an upper bound include simply taking the best ROI in each row. In our current example, this approach will give an invalid solution (see the light grey boxes below in Table 5-6 where Karissa is assigned to two projects) but we can be sure that the optimal solution will not be better than this average return of 35.22%. Similarly, a lower bound can be found by taking the minimum in each row. This will also be an invalid solution as Amy and Carl are each given two projects, but, using this as a worst-case scenario we can be sure that any valid solution will not give an average return on investment below 26.95% (see the dark grey boxes in Table 5-6). Students can then tweak these solutions or apply a guess-and-test method to find a reasonably well-performing valid solution. The optimal answer via the Hungarian Method is having Karissa assigned to the Manufacturing project, Abdul to Management, Carl to Construction, and Talah to Research with Amy being left unassigned. The optimal solution gives an average ROI of 34.975%; a value very close to our rough estimate of the upper bound of 35.22%.

Table 5-6: Estimating a Reasonable Maximum (light grey) and Minimum (dark grey) through Simple Decision Rules

	Karissa	Amy	Abdul	Carl	Talah
Construction	36.6	31.8	32.2	35.6	32.4
Manufacturing	42.4	31.1	41.1	32.7	40.8
Management	30.3	25.5	32.9	22.4	31.4
Research	27.6	24.1	25.2	22.5	29

5.7 Results: Creation and Exploration of Models Increases Conceptual Understanding

After several of these modelling labs were complete, students were given qualitative case studies to test their conceptual understanding of these same models and their ability to categorize the problem appropriately (see Appendix 7). The case studies were series of realistic engineering consulting scenarios where students were asked to describe the goals, constraints, key variables, and strategies for the situation and make an attempt to categorize the case study as one, many, or none of the categories discussed throughout the semester (see Appendix 8 for the summaries of each problem type in terms of GCVS given to the students at end of each associated lecture). The assignments were designed to be classified as one of the models of interest for which the students had already completed a numerical lab assignment (however, of course, alternate defensible classifications were accepted). The intended categories for these four assignments were: process flow, queuing, inventory, and a facilities design respectively. In the final case study, students did not have an associated facilities design lab assignment but did have lectures like those given for the other topics including summary data on problem categories (again, see Appendix 8 for more details).

The form and content for these case studies was somewhat foreign to students so it was expected that, over time, familiarity with the case-study structure would progress and student scores would increase. This initially seemed to be the case, although the trend did not continue with the final assignment: we see a precipitous drop in performance for Case Study 4 (Figure 5-9).

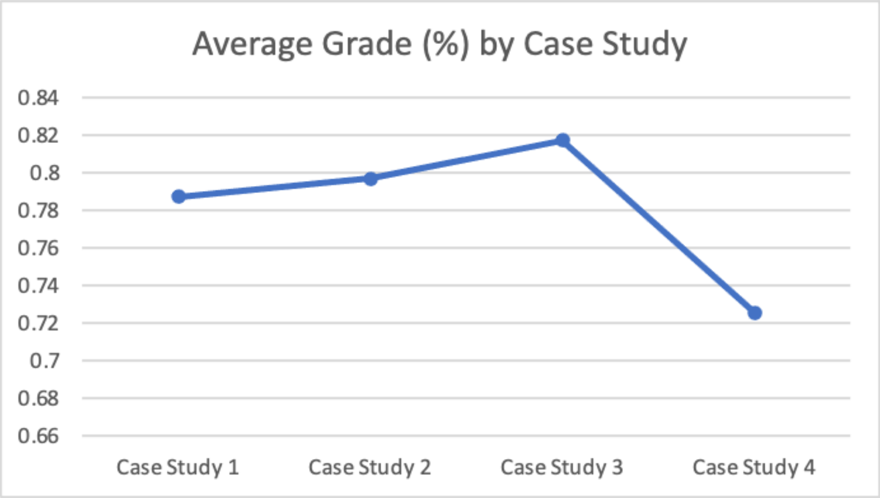


Figure 5-9: Average Grade as a Function of Case Study Number

Hypothesis tests were completed to determine if there was evidence to suggest that the average scores for Case Study 4 were statistically lower than the others. To avoid the familywise error-rate problem, we compared the performance of the last case-study to that of the next-worst performing case study (the first assignment). We reason that if we have evidence to suggest that the performance was worse for Case Study 4 than for Case Study 1, likely it would also be for the other two case studies. Our null hypothesis is then $\mu4 - \mu1 \geq 0$; the alternative being $\mu4 - \mu1 < 0$. The resulting p value was 0.0546.

Enrollment in the study was lower than what was hoped (57 students could have opted into the study), and despite several attempts at increasing enrollment, recruitment plateaued at 14 participants. Given the constraint of the available sample size an $\alpha = 0.05$ gives a Type II error rate of $\beta = 0.65$. If we use an $\alpha = 0.10$ we have a β of 0.51. Although the risk of a Type II error is quite high in either scenario (incorrectly failing to reject the null hypothesis) the latter scenario gives a better balance of Type I and Types II error rates. If we accept this argument (Lavrakas, 2008; Lakens et al., 2018), then we would state that the null hypothesis is rejected and there is evidence to suggest that students performed more poorly on Case Study 4 than on the worst performing of the other three case studies.

5.8 Interpretation of Results

The authors interpret these results to mean that when students were asked to create models for the numerical and contextual lab assignments, their conceptual understanding of those models ameliorated and they could begin to "chunk" the details of each type of problem together and register it as a pattern or schema in their memory. This chunking of these design prototypes enabled them to perform fairly well in the first three case studies. However, the sudden drop in performance for the final case study is thought to be caused by the fact that they did not have experience completing a detailed numerical Facilities Design lab assignment. In other words, students had less experience to draw upon when attempting to categorize that last assignment: they did not recognize the pattern as well as they did in the previous three assignments. Students were only given the design prototype in terms of GCVS listed in prose during the lecture on Facilities Design. While perhaps valuable declarative knowledge, it seems that the lecture did not give them enough understanding to "chunk" the concept as well as those topics which had an accompanying assignment.

Of course, there are other possible interpretations: it could be that since this was the last case study of the semester the students ran out of time to complete it well. It could also be, perhaps, that the nature of the facilities design model was more complex or difficult to understand for this group of students than the other models.

To improve the course offering for next year, we sent out a brief survey to students. Of the 17 respondents (out of a class of 57), only five individuals stated that they performed worse on this final case study than the previous three assignments. Students were given the opportunity to select why they thought they performed worse from a set of five options (the fifth option being "other"), their opinions were spread somewhat evenly (see Table 5-7). While a sample of 17 can be helpful in informing course design, the subset of five students who performed worse on this final case study is very small and so the submitted responses will be considered with great caution.

Table 5-7: Student Opinions Regarding Why They Performed More Poorly on the Final Case Study (Five Respondents)

Self-Reported Reason for Lower Performance (Multiple Responses allowed) by 5 Respondents	Response Count
It was the end of semester, and I ran out of time	2
The content was harder or less familiar for Problem Definition #4 than the other Problem Definition assignments	4
It was harder to read and understand Problem Definition #4 than the other Problem Definition assignments	2
The other Problem Definition assignments had numerical lab assignments that covered similar topics but this one did not (i.e. there was no facilities design lab assignment)	2
Other (students able to fill in a custom answer here)	0

Although the responses are far from definitive, we interpret this to mean that it is likely the end-of-semester rush was, at least, not the clear and decisive reason for the decrease in grades according to student self-reports. This seems to agree with the instructor's understanding of student experience: the time given to complete these assignments appeared to be sufficient and very few requests were made for extensions for any of the case studies throughout the semester. It could be that most students found this "harder and less familiar" simply because they did not get a chance to interact with the model like they did with the subject matter of the other three case studies (Process Flow, Queuing, and Inventory). Again, the sample size is quite small here to make reasonable claims, so further study will be required to answer questions that arise from this initial work. Further work to address these questions is described in Chapter 6.

However, it is believed that the drop in performance was due to, at least in part, the lack of opportunity students had to "playfully" model the facilities design problem numerically. There are studies that suggest that conceptual misunderstanding in engineering (and perhaps many other fields as well) is indeed caused by lack of direct experience with the content being studied (Streveler et al., 2008). An argument could be made as well that the work by Getzels and Csikszentmihalyi (1976) many years ago showed that artists who "played" with their subject matter for long periods before proceeding with their drawings had a far better understanding of the concept they were trying to communicate than their counterparts who did not explore their raw material for very long or at all.

5.9 Future Work

To help respond to questions raised above, the next chapter will detail case-study performance data from students in more senior years of the engineering program to compare with the data shown here. In addition, in the next academic year, the new second-year student performance will be compared with the data seen here. They will again be given similar case studies, but this time in a different order, and this time with a numerical lab assignment for facilities design. With these and other changes we should be able to better understand where the differences in performance come from.

As results (hopefully) become more conclusive, we wish to focus more specifically on the elements of instruction that seem to be most successful in improving conceptual understanding and pattern recognition and determining their relative effectiveness. The interventions of interest include lectures, relatively straightforward "plug-and-chug" numerical examples (as in typical end-of-chapter questions), exploratory numerical model creation (as detailed in this paper), and even use of the conceptual assessment tools themselves (the case studies detailed in this chapter).

5.10 Summary

This chapter has described the creation of an introductory course in IE which categorized key problems in terms of their GCVS as well as gave students opportunity to create and explore basic models. The purpose of the course was to give students experience in creating fundamental models in IE to enable them to better understand the concepts behind the models as well as how to choose which model to use (pattern recognition) in realistic contexts. Student scores on case-study assessments suggest that engaging in an exploratory modelling task does increase the ability of students to recognize when a model is appropriate for a given scenario. The authors plan future work that will continue to pursue this question and clarify what elements of instruction and modelling are most responsible for increasing student ability to diagnose problems.

Chapter 6 – PROVIDING NOVICES WITH A UNIVERSE OF PROBLEMS IMPROVES PROBLEM DEFINITION[10]

6.1 Chapter Summary

It was proposed in Chapter 4 that expert schemas should help novice designers diagnose design problems. This claim was tested in Chapter 5 by providing second-year engineering students with expert schemas for seven different types of Industrial Engineering problems in the form of lectures and modelling assignments. Results suggest that when students were provided with the modelling exercise they performed as well as more experienced undergraduates in a problem-definition task. However, when students did not model design prototypes, they performed more poorly than their more-experienced counterparts scoring approximately 9.6% lower in the problem-definition case studies. The study described below suggests that, through the practice of modelling, novices can better recognize expert problem categories.

6.2 Background to the Study

This study is the logical result of the previous chapters. The key finding of Chapter 2 was that, according to anthropologists who study engineering students, some cultural issues can be mitigated by teaching young engineers how to define their problems well. While the practices suggested in Chapter 3 are not being tested, a related practice more directly associated with Chapter 4 is. This chapter noted that problems can be described in terms of Goals, Constraints, Variables, and Strategies (GCVS). Here, it was also suggested that defining a Universe of Problems (or design prototypes) for novices should help them in the task of problem diagnosis. Chapter 5 then described an introductory course in Industrial Engineering (IE) which was created to introduce key design prototypes for IE, through the means of lectures and exploratory modelling assignments. Initial data analysis suggested that problem diagnosis tasks were performed better when students were given exploratory modelling assignments related to a particular

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[10] A version of this chapter has been submitted to a journal for peer-review.

problem than when they were not. This raised several questions which are to be further explored in this chapter.

6.3 Purpose of this Study

The purpose of this study is to further investigate what sorts of interventions help students diagnose problems well. While Chapter 5 seemed to suggest that including an exploratory modelling task significantly improved performance, more examination was required. That is, when a second-year class was considered in isolation, their performance on the final case study was far worse when compared with their previous three case studies. Questions were raised about the source of that statistical difference: it may have been due to the timing of the intervention (end of semester) or perhaps the difficulty level of that final case study. The work described below was meant to begin to address these concerns.

6.4 Study Method

In this section the study method is described: in short, students over four years of the IE program (years two through five) were given the same case studies and asked to answer seven short-answer questions. These questions were graded, and their score was treated as a metric of their problem-identifying ability: a higher score indicated a greater understanding of the case study and its fit into a prototypical problem category.

6.4.1 Identifying a Universe of Problems (UOP)

The idea of the Universe of Problems was taken from Marshall (1995) and her work in the teaching of mathematics although similar ideas have been used in medical education (Beck & Bergman, 1986; Groen & Patel, 1985). The basic idea of the UOP is that each discipline has a key set of problems, that if well understood, can help novices understand the discipline well and discern what tools and models to use to solve the problem appropriately. It is not proposed, however, to drive this theory to its extreme and suggest that every engineering design problem can be solved with a template. It is claimed here, rather, that the Pareto Principle applies, and that knowledge of the several most common sorts of problems should be very helpful to novice problem-solvers just entering into their field. Studies in the medical domain have shown this (Groen & Patel, 1985) and we expect the same could be shown in engineering.

Gero (1990) posits that experts have these "UOP" in their mind (he calls them design prototypes), and this is a key reason as to why experts are able to more effectively begin designing with incomplete information (Gero, 1990). It was argued in Chapter 4 that design prototypes should help novices act like experts in performing breadth-first approaches to problem definition (Cross, 2004) as opposed to their typical ineffective depth-first (guess-and-test) approach (Ahmed et al., 2003).

In order to select a reasonable set of design prototypes several sources were consulted: introductory texts in IE (Atkins, 2019; Shtub & Cohen, 2016; Turner et al., 1992), curricula of similar programs (Georgia Tech, 2021; U of T, 2021; Concordia, 2021), and the content of final-year design projects at our institution. In the end, the key problems in Industrial Engineering were chosen to be quality control, inventory management, process flow, queuing, human factors, linear programming, and facilities design (see Chapter 5 for more details). Once these seven topics were chosen, modelling lab assignments were created to help students understand and "see" the problem models in action. After students attended lectures and completed the lab assignments, four qualitative case studies were given to assess student ability to choose appropriate design prototypes for a particular fictitious case study context.

6.4.2 Study Design

Students in second, third, fourth, and fifth year of our program were given identical case studies to assess their ability to diagnose a described system as suffering from a given type of IE problem. Volunteers from IENG 2201, IENG 3345, IENG 4480, and IENG 4581 were asked to opt-in to the study, and if they did so, they received a $5 coffee card. The opt-in rates varied from 25%-50% (see Figure 6-2). These classes were not all held in the same semester but in Winter 2021, Summer 2021, Winter 2021, and Fall 2020 respectively. All classes were taught, and all deliverables were submitted online due to the ongoing pandemic. The second-year class (IENG 2201), however, is planned to be delivered online for the foreseeable future whereas the rest are expected to return to in-person classes as soon as possible.

All students were given the same case studies, and all given the same information regarding the rubric or grading scheme (simply that it was worth 2.5% of their grade and that short answers/bullet points were appropriate for their solutions). Only the second-year students were given the laboratory exercises and then given case studies after four of the six labs were completed. All lab assignments were corrected by markers, but all case-study grading was done by the researcher with a standardized rubric and the researcher was never made aware of who was in the study. A Research Assistant (Ms. Ana Carvalho Bianco) was responsible for presenting the opportunity to opt-in to students and also extracting their data if they decided to opt-in. Twenty of the respondents identified as female while 69 respondents identified as male. Thirty-five volunteers identified English as their second language, 53 as their first, and one as their third. The RA did not release sample data to the researcher until all final grades for any given course were released. The recruitment materials are in Appendix 9 and this study was approved through the Dalhousie Research Ethics Board file number 2020-5331.

The second-year class served as the "experimental" group. This group of students was given lectures on the various sorts of IE problems covered, summary of key aspects of the problems (their goals, constraints, variables, and strategies for next steps – referred to as GCVS), and exploratory lab assignments. The second-year students, however, were given lectures and a summary of the Facilities Design Problem in terms of GCVS as usual but not the exploratory modelling lab assignment. The students in the higher years of study, although differing in level of IE experience, served as a control group, and were not given any teaching interventions. Statistical analyses were performed to test whether experience or the interventions influenced performance.

6.5 Results and Discussion

This section is broken into two subsections. In the first subsection, data collected in the experiment is described and explored through various visualizations. In the second section, results of hypothesis tests are reported, and conclusions drawn.

6.5.1 Data Visualization

In Figure 6-1 we see the progress of each class as they move through their case studies in chronological order. Although a different and unrelated IE problem is covered in each case study (the Process Flow Problem, the Queuing Problem, the Inventory Problem, and the Facilities Design Problem), there is a pattern in performance: increase, increase, drop. In our fifth-year student data, however, we see that the pattern does not hold; for some reason the second (Queuing) assignment shows a very large dip in the average grade.

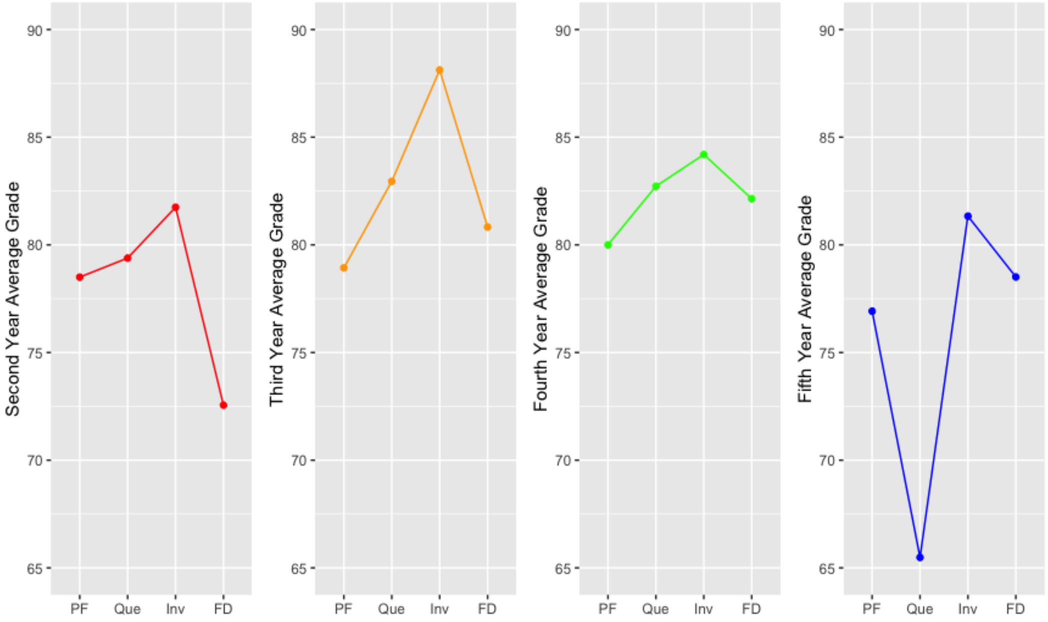

Figure 6-1: Case Study Performance by Year; Sample Sizes: n = 16, 15, 32, 26 respectively

After exploration into the possible cause of this drastic decrease in performance, it was found that the fifth-year students did not receive feedback in a timely manner for their first assignment. Unfortunately, detailed notes from their marker regarding the correctness of student responses in the Process Flow assignment were only returned hours in advance of the Queuing case study being due. However, in all other instances for all classes, results were given at least one week in advance of the next case study's due date. By the time the fifth-year students received their feedback from the Process Flow assignment, many of them had already submitted their Queuing assignment, and many others would not have had much time (a matter of hours) to incorporate the feedback given, if at all. Due to this error in procedure, the data was left out of some of the analysis (see Sections 6.7 and 6.8).

Another surprising characteristic seen in Figure 6-1 is the spike in third-year performance for the Inventory case study. The very high average (87%) was surprising as it was expected that the third-year class would perform similar to or more poorly than their fourth- or fifth-year counterparts. To aid in exploration of this matter, the instructor of the third-year course was asked to share the class averages for their assignments (no individual data). They agreed (along with the other instructors – one of the authors being one of these instructors) and population and sample means are plotted below in Figure 6-2. Note, however, that ethics approval was not granted for analysis of the population but only the sample data.

Figure 6-2 was drawn to visualize if there was an obvious difference between the sample average scores and the population average scores. For most classes, the sample averages (solid line) were slightly above the overall class averages except in the case of the fifth-year class. However, the difference between population average and sample average is relatively extreme for the third-year class; especially for the Inventory assignment. One last difference should be noted: although, for the most part, the fifth-year sample data follows very closely the population data, the decline in grade for the last assignment is markedly less in the population data than the sample data.

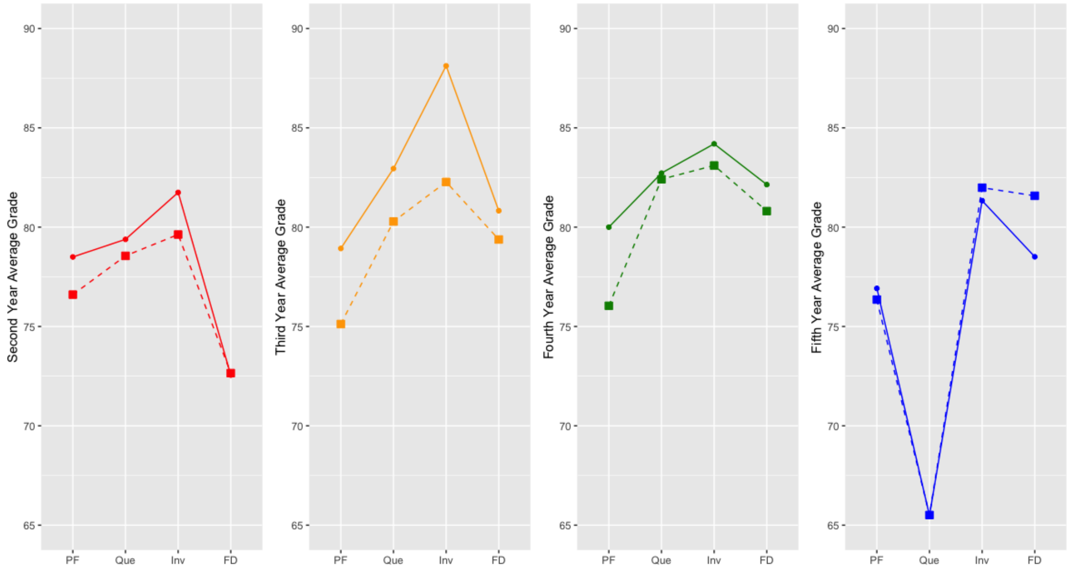

Figure 6-2: Case Study Performance: Sample Averages (solid line), Class Averages (dashed line). Sample Sizes: n = 16, 15, 32, 26, Population Sizes: N = 53, 61, 60, 65

In Figure 6-3, all sample data are superimposed on the left pane, and the population data on the right (with the accidental no-feedback condition removed from the visualization). The population data illustrates the performance on the first case study was very similar across all classes. Progressing from left to right, it appears the third-, fourth-, and fifth-year data clumps together nicely while the second-year students slowly drift lower. The final assignment shows a very sharp decline in performance for these second-year students. It is believed that this is due to the exploratory lab assignment intervention being removed.

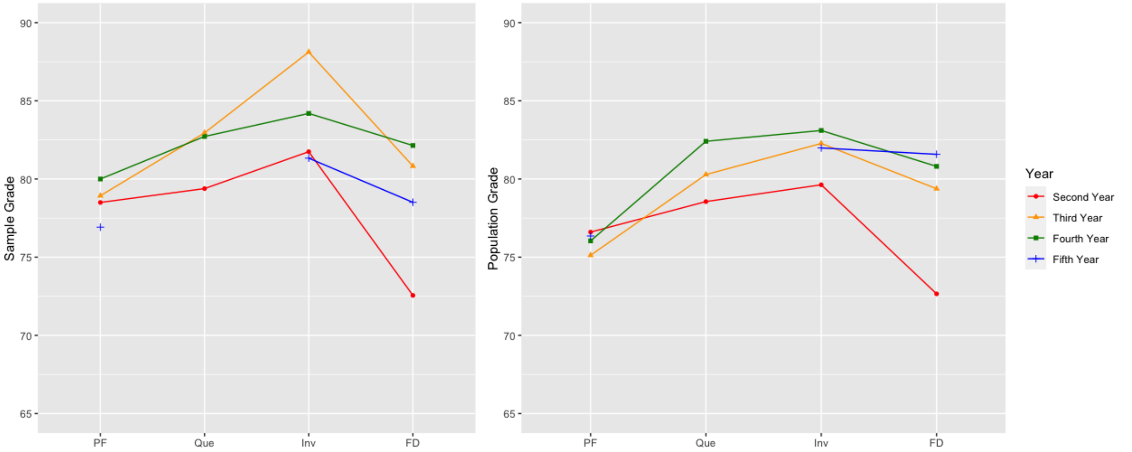

Figure 6-3: Sample and Population Case Study Performance by Year. Sample Sizes: n = 16, 15, 32, 26 Respectively; population sizes: N = 53, 61, 60, and 65 Respectively.

In Figures 6-4 and 6-5 the performance drop from Assignment 3 to Assignment 4 is explored. In Figure 6-4, the datum is the first assignment grade for each year of study. As one scans the figure from left to right, we can see at least two patterns: (1) the magnitude of the drop appears to decrease steadily as year of study increases; and (2), the drop in performance in the final case study by those in their second year (who did not get an exploratory Facility Design lab) is greater than the others. This drop by the least-experienced students is the only class where the final assignment average is below the first assignment average. Note: like Figure 6-2, the no-feedback assignment for the fifth-year class (queuing) has been removed.

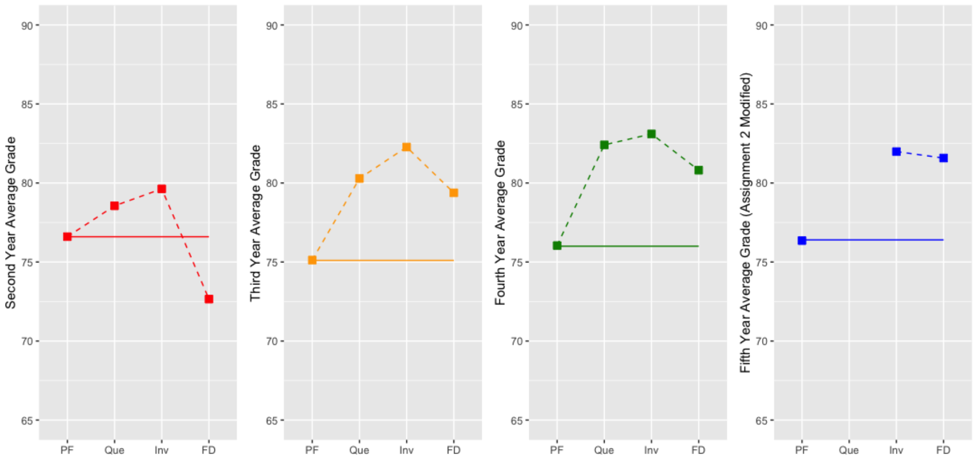

Figure 6-4: Visualizing the Drop in Average Assignment Grade for the Final Assignment as Compared With Performance on the Initial Case Study (PF). Note: Queuing Assignment Data has Been Removed for the Fifth-Year Class Here for Reasons Stated Above

Figure 6-5 was created using Assignment 3 as the datum; a small solid line was drawn from the Assignment 3 (Inventory) location forward to the Assignment 4 (Facilities Design) location on the graphic. This datum makes the magnitude of the observed drop in A4 performance obvious. The specific differences between the average population scores on Case Study 3 (Inventory) and Case Study 4 (Facilities Design) are 7.0, 2.9, 2.3, and 0.4 for years two, three, four, and five respectively. This figure suggests that not having experience with a numerical lab assignment significantly affected the performance of the second-year class, and that each additional year in the undergraduate program seems to have mitigated the severity of the drop in grades.

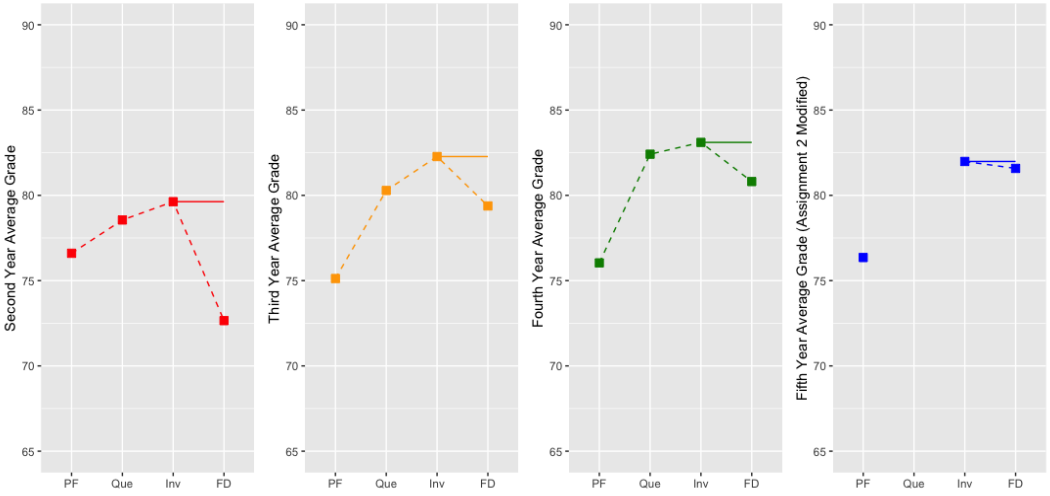

Figure 6-5: Using A3 (Inventory) as a Datum to Highlight the Magnitude of Drop in Score From A3 to A4 (Facilities Design).

6.5.2 Data Visualization Summary

In this section the case-study performance data was explored with simple visualization techniques using both sample and population data from the study. In general, it showed that the data follows a mountain-shaped curve where there is a steady increase in the performance over the first three assignments, but a (by times sharp) decline in performance for the last assignment. Some surprises were visually highlighted: A3 population scores for the third-year class was markedly lower than the sample scores, A4 population scores declined less than the sample scores for the fifth-year class, and A2 for the fifth-year class dropped very low – after looking at instructor records – due to lack of timely feedback.

Illustrations suggest, by using A1 and A3 as baselines, the A4 performance decline for the second-year class was far steeper than the rest, and the decline in performance for the fifth-year class was far less than the rest. It is suggested that lack of experience "playing" with the somewhat open-ended numerical lab assignment was the reason for the steep decline in second year; conversely, it is posited that additional years of experience with the Facility Design problem is the reason for the absence of the sharp decline in final assignment performance of fifth-year students.

6.6 Statistical Analysis

Given the background above and in Chapter 4, the following statistical questions are asked of the data:

i. Do the lectures and exploratory lab assignments result in the second-year class performing as well as the more experienced classes in the first three case studies?
ii. Does the lack of an exploratory laboratory assignment in the fourth case study cause performance to deteriorate for the second-year students?
iii. Is there a difference in performance as a function of experience (e.g. year of study)?

6.7 Answering the Questions

To answer these questions simple t-tests were performed. Ideally, a comparison would evaluate the performance in every class to every other class for each set of data.

However, such an analysis is subject to "familywise error rate," where the more comparisons one makes, the greater the risk of falsely rejecting at least one null hypothesis. There are ways to circumvent this problem while still making multiple comparisons (e.g., the Bonferroni Correction), but this requires testing each comparison at the α/N significance level where N is the total number of comparisons. The small sample sizes in our study makes it problematic to make test at α/N as this increases the probability of Type II errors and makes it increasingly difficult to reject the null hypothesis. Accordingly, it was decided to simply avoid making multiple comparisons as much as possible. This meant that for each set of assignment data the second-year students would only be compared against the most experienced student group. Table 6-1 shows the results of the t-tests performed on each set of data.

It should be noted that the same process for using these statistical methods was taken here as was detailed in (Lavrakas, 2008): the data was checked for normality before t-tests were performed. The Shapiro test was used to do this, and only the final assignment in fifth year failed this test. For this reason, in Case Study 4, the second-year class was instead compared to the next most experienced group: the fourth-year class. The reader should also be reminded that, due to the poor performance of the fifth-year class in the second assignment due to lack of timely feedback, the fourth-year class was chosen to be representative of the most experienced class for this second assignment as well.

Table 6-1: T-test Results for Each Dataset

Dataset	Hypotheses	p-value
Case Study 1 (Process Flow)	H_0: $\mu_{SecondYear} - \mu_{FifthYear} = 0$ H_a: $\mu_{SecondYear} - \mu_{FifthYear} < 0$	0.36
Case Study 2 (Queuing)	H_0: $\mu_{SecondYear} - \mu_{FOURTHYEAR} = 0$ H_a: $\mu_{SecondYear} - \mu_{FOURTHYEAR} < 0$	0.20
Case Study 3 (Inventory)	H_0: $\mu_{SecondYear} - \mu_{FifthYear} = 0$ H_a: $\mu_{SecondYear} - \mu_{FifthYear} < 0$	0.54
Case Study 4 (Facilities Design)	H_0: $\mu_{SecondYear} - \mu_{FOURTHYEAR} = 0$ H_a: $\mu_{SecondYear} - \mu_{FOURTHYEAR} < 0$	0.01

Below in Figure 6-6, we see the boxplots comparing the second-year class with their more-experienced counterparts. In the first three assignments the difference in the (sample) median grade ranges from approximately 2.5 to 5 percentage points. The difference in the median grade for the final assignment, where second-year students did not complete an exploratory lab assignment, was approximately 14 percentage points. Table 6-1 illustrates that there is insufficient evidence to reject the null hypothesis until the final case study. The hypothesis test for this final case study (Facilities Design) reports a p-value of 0.01, and so we have strong evidence to reject the null hypothesis that the second-year and fourth-year class showed the same performance. The 95% confidence interval for the difference in means is (2.63, ∞), with the sample difference in means being 9.6%.

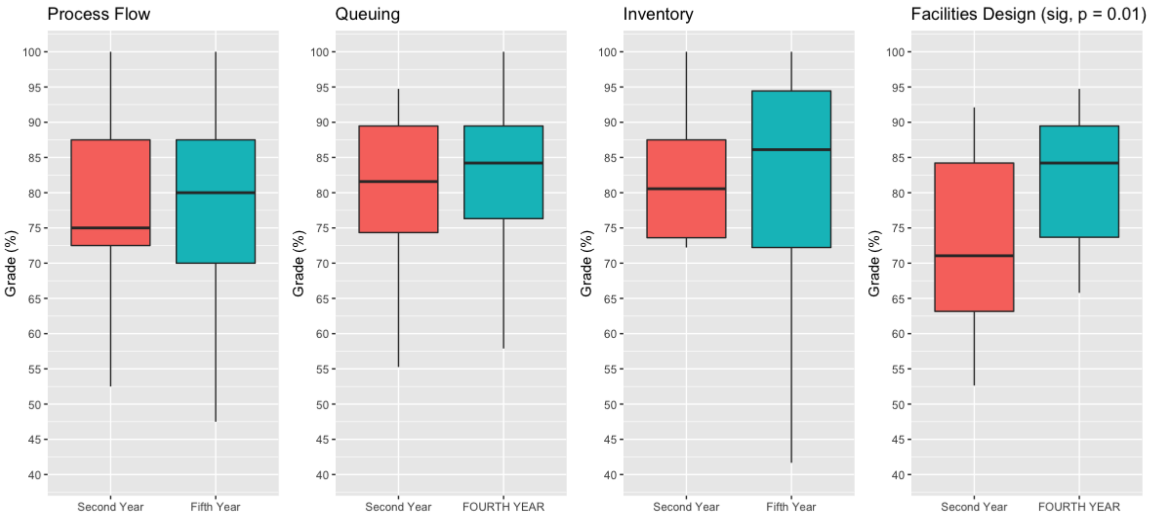

Figure 6-6: Boxplots for Second-Year Performance as Compared to Their More-Experienced Counterparts

A note regarding significance level: although an α level of 5% is typical in statistical analysis, the authors chose to use an α of 10%. The authors justify this for at least two reasons: (1) Use of 10% is not uncommon in statistical analyses (Lavrakas, 2008), especially when sample sizes are small and when there is not a great level of control over the experiment (participants in our study were spread out over the school year and competed their assignments in whatever environment, and during whatever time period was suitable to them); (2) balancing Type I and Type II error is both reasonable and encouraged (Lakens, 2018). This being said, our very low p-value of 0.01 renders this discussion somewhat academic.

6.8 Minimizing the Removal of Data

It was thought that experience would play a larger role than the statistics have thus far showed. The visuals suggest (see Figure 6-3) that there may be a modest increase in performance due to experience in Case Study 1 through Case Study 3, but there is no evidence in the statistics to suggest there is a difference in mean score between the most junior and most senior classes over these same assignments. Given this result, the search for difference in performance due to experience level was abandoned. With no discernable difference shown between the more-experienced groups, it was no longer necessary to keep them separated. It was thought that statistics could again be performed, now with larger control groups and with removing as little data as possible to increase confidence in the results.

In this slightly different organization of the data, the second-year class is considered the experimental group since they received special instruction and tailored lab assignments. The other students in years three, four, and five are considered the control group: they received neither of these interventions. As previously, normality tests were performed. However, in this case all the control groups failed the normality test, not just the fifth-year class. Now it was not possible to use t-tests to compare the data. Instead, the non-parametric Wilcoxon rank sum test was used to determine if there was sufficient evidence to reject the null hypotheses that the compared medians were the same. The resulting p-values are shown below in Table 6-2.

Table 6-2: Results When Data Grouped as Experimental (Year Two Students, n=16) and Control (Years Three, Four, and Five, n=73)

Dataset	Hypotheses	p-value
Case Study 1 (Process Flow)	H_0: $M_{\text{exp}} - M_{\text{control}} = 0$ H_a: $M_{\text{exp}} - M_{\text{control}} < 0$	.38
Case Study 2 (Queuing)		0.20 (.78 if fifth-year included)
Case Study 3 (Inventory)		0.13
Case Study 4 (Facilities Design)		0.01

As in the previous approach, the null hypothesis is not rejected until the final case study, but this time no data was removed due to their failing a normality test. Also, as we see in row two of Table 6-2 above, whether the non-feedback group for Case Study 2 is included or not, the null hypothesis will not be rejected. The 95% confidence interval regarding the difference in median grade is (2.63, ∞) with the difference in sample medians being approximately 12%.

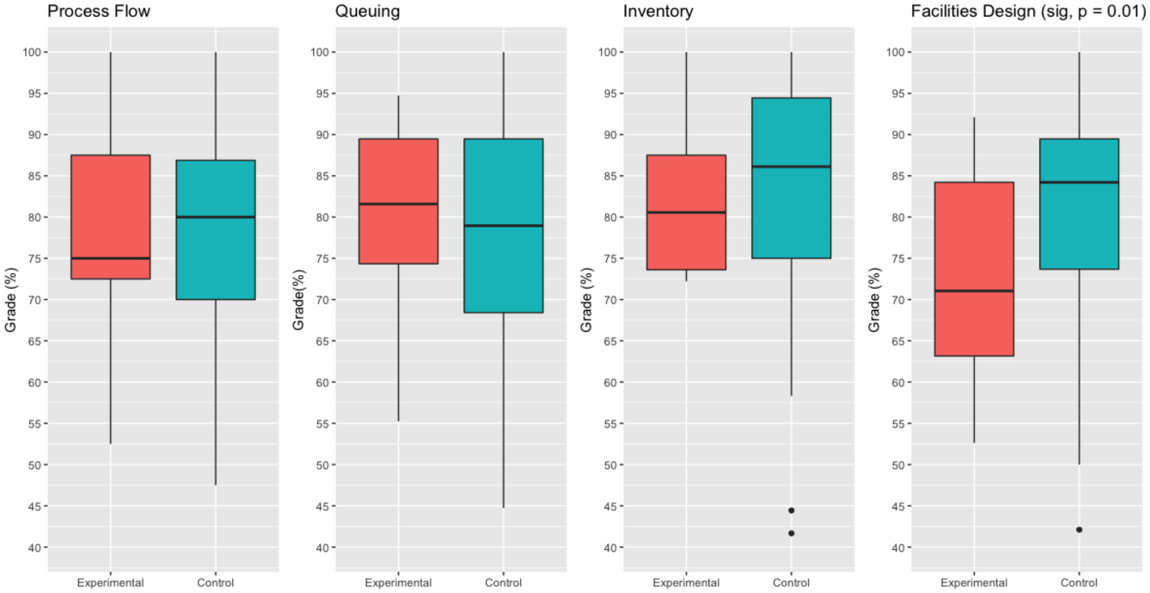

Figure 6-7: Differences in Means if All More-Experienced Groups are Considered the Control Group

In Figure 6-7, we notice a similar pattern as in Figure 6-6: the differences in median are around five percentage points except for the final case study where it increases to about 14 percentage points. We may also notice, however, that Case Study 2 is somewhat anomalous once more. The lack of feedback for the fifth-year group has pulled down the median for that control group. While the goal was to use all data available, it was realized that the no-feedback group could be skewing the results in the direction which was preferred (i.e., resulting in the conclusion that second-year students and more experienced students performed equally well in Case Study 2 when perhaps they did not). To work against this bias, the fifth-year data can be removed to see if the resulting increase in the performance in the control group has any effect. However, the p-value of 0.20 still results in insufficient evidence for the null hypothesis to be rejected (see Table 6-7). The visual corresponding to this new scenario now follows the usual pattern of the control group reporting slightly better performance than the experimental group for the first three assignments, but then markedly better for the final case study (see Figure 6-8).

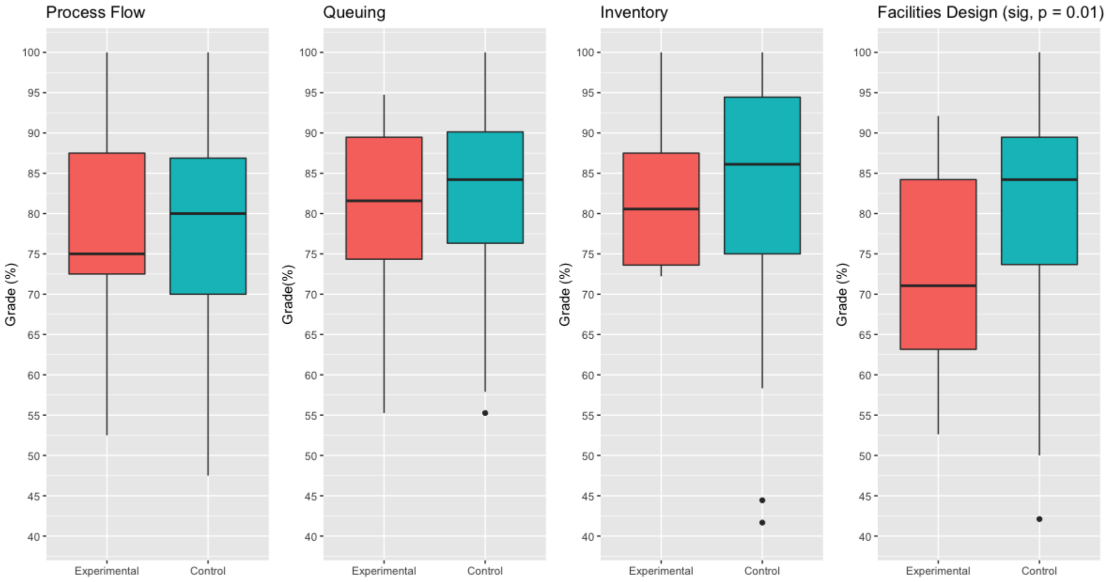

Figure 6-8: Differences in Group Performance With the Non-Feedback Group Removed (Fifth-Year Students From the Queuing Assignment)

Lastly, one may notice the similarities in Figure 6-6 and Figure 6-8. Juxtaposed in Figure 6-9, the two different sorts of control groups are shown side-by-side. Figure 6-9 illustrates that the inter-quartile ranges and max and min values are quite similar when all upper-year classes are included as the control group (left) as opposed to only including the most experienced group (right). Figure 6-9 suggests that whether the control group comprises individual groups or all non-intervention groups together, their distributions are quite similar. In effect then, either one of our shown statistical approaches result in the same conclusion: the null hypothesis is not rejected until the final case study.

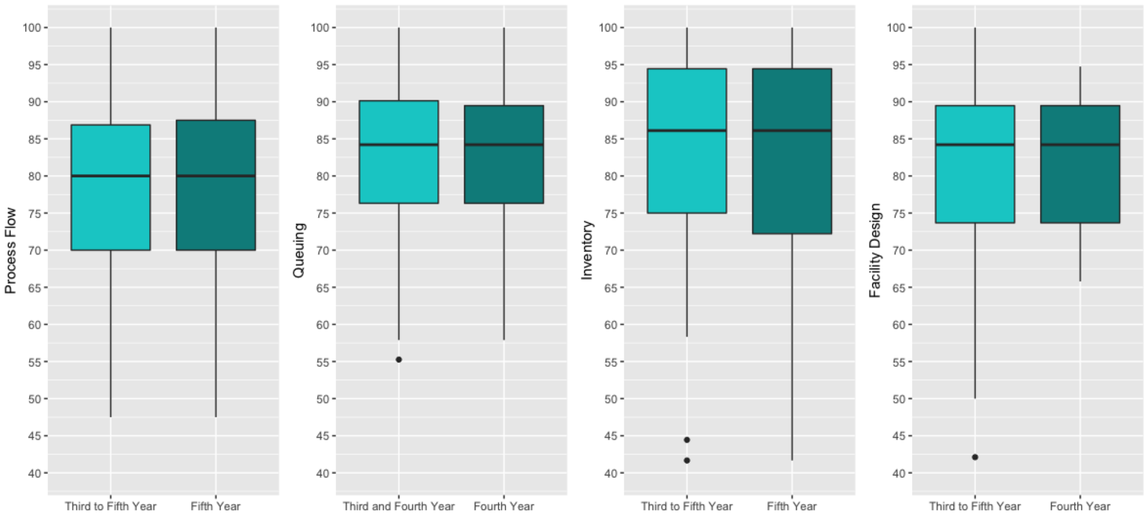

Figure 6-9: Comparison of the Control Groups: All Experienced Students on the Left; Only the Most Experienced Class on the Right

6.9 Limitations of the Study

Like any work, this study has its limitations. The most significant concern may be that experience and the intervention were confounded. The intervention was removed but it was not given to another set of second-year students in order to develop a baseline performance. Instead, it was compared to more experienced students who had passed their second year (which again is of note, as transition from second- to third-year requires a more rigorous academic standing than from first- to second-year). In addition, these data were gathered from students in their natural environment – not a strictly controlled environment. This means students did not have to complete the case studies at the same time of day, in the same location, or without discussing with their classmates. These other factors could have played a role. The order of the case studies could also have influenced performance – perhaps the drop in score was simply due to the Facilities Design case study being given last. Also, the Facilities Design problem could simply be harder than the rest –this could have caused the novices to be more greatly affected than the rest. In addition, the term “experts” may not be entirely appropriate here. Of course, fifth-year students are more experienced than their second-year counterparts, but experts, likely not. Lastly, enrollment in the study was low and it was during a pandemic year which may affect the author’s conclusions.

Given these limitations it may be possible to interpret the results differently. One may offer that the data suggests that neither the intervention nor the first two years of study improve performance in a problem diagnosis task. However, for this to be true, we would expect that performance in all four case studies to be worse for the novice students – not just the last one. Then one may argue that it was because the case study of interest was last that it showed the poorest performance. Conceivably so, but the Facilities Design case study was completed last for all four classes. Indeed, this may be why there was a drop in performance for all classes – all case studies were completed the end of term. This goes also for the theory that the Facilities Design concept was just more foreign or harder for students to grasp. Feasible as well, but this same difficulty would be borne across all of the four years. This being said, it is conceivable that the difficulty of this particular case study was more severely felt for our second-year students. To address these most significant limitations, a study is already underway to test another group of second-year students to complete the case studies, but this time for a different topic (not Facilties Design) and also not at the very end of the semester. This will hopefully resolve these issues highlighted just above and also enable the author to compare second-year students against second-year students (all from pandemic years).

6.10 Conclusion

Although the study has some limitations, the author suggests that this work supports what the literature suggests: when novices are provided with expert schemata their performance increases. In this case, the schemata, alternatively called the “universe of problems” or “design prototypes,” were explicit outlines of the important structural elements of common problems in Industrial Engineering. The design prototypes were introduced in two basic forms: (i) descriptions of the problems in prose form, described to the students in terms of their goals, constraints, variables, and strategies (GCVS); and (ii), in numerical case-study form (laboratory assignments). When novice students were given these lectures and modelling assignments, they performed as well as experienced undergrads in a problem-diagnosis task. However, when they were not provided with the chance to explore numerical models, they performed significantly worse than their more experienced counterparts (by 9.6% according to our sample data).

6.11 Future Work

The exploration detailed above has raised many questions which the authors plan to follow up in future work: (i) in the short term, execute a study that addresses key limitations; (ii) Plots suggest that performance in the problem-diagnosis task increases with experience; can we find statistical evidence that upper years (years three, four, and five) differ in performance? How much do they differ as compared with early-career professionals? Late-career? (iii) Interventions: the intervention of an exploratory lab assignment has been shown to make a significant difference in the problem-definition task; will other interventions such as traditional end-of-textbook assignments or the GCVS lectures also show this?

Chapter 7 – CONCLUSION

7.1 Thesis Summary

This thesis has shown that the problem definition stage of the engineering design process is important, underdeveloped, and that the Universe of Problems approach can help students define problems well.

There is currently a problem with problem definition. There are likely other factors as well, but engineering culture has made the practice of defining the problem difficult to incorporate into engineering curricula. From a cultural perspective, engineering is dominated by the image of engineer as problem solver. This can be seen in the propensity students have in attempting to solve a problem before they have a big-picture concept of what the current system dynamics are. They also, paradoxically, feel resistant to open-ended problems yet also frustrated with not being prepared for “the real world.” The result is underprepared engineers who can waste resources, but more importantly perhaps, unwittingly cause significant social harm. Problem definition, therefore, must be central in engineering curricula.

Currently, problem definition is not well-covered in engineering education. The survey of design texts described in Chapter 3 illustrates that problem definition is often overlooked or minimized. Many quotations exist with regards to the importance of problem definition, but not much substantial work done with regards to how to teach it. The content of Chapter 3 is a response to this need and suggests that the most promising interventions from Requirements Engineering that could be used by engineering as a whole. The most fruitful methods seem to be prototyping, contextual inquiry, and group elicitation techniques. These findings aside, there is still difficulty in differentiating between the product and process of problem definition and the product and process of requirements listing.

Chapter 4 introduced the idea of the Universe of Problems Approach which is a process for helping novice designers produce a problem definition. This method is based on research into novice and expert performance: experts “chunk” problems in their area into basic categories (called schemes or design prototypes) and they use these categories to perform breadth-first search strategies when defining problems. Therefore, it was believed that providing students with an expert-like categorization scheme should help novices behave more like experts. Chapter 5 was a description of an introductory course using seven models to make up a reasonable Universe of Problems in IE. Students were taught the design prototypes in lecture form but also given "exploratory" lab assignments. These labs were meant to give students a chance to "problem find" in a different manner: through experience creating and modifying the same models they were hearing about in declarative language. Initial statistics on novice (second-year) performance suggested that the exploratory lab assignments made a significant difference in their ability to diagnose problems.

Chapter 6 was a more comprehensive treatment of the question if novice performance could be ameliorated with expert design prototypes. Student performance in a problem-diagnosis task in year two was compared with performance in years three, four, and five. When year-two students were provided with lectures and exploratory labs, there was no evidence to reject the null hypothesis that they performed any differently than more experienced students. However, when year-two students were only provided with lectures, there was enough evidence to reject that their performance was the same as that of the upper-year classes. The actual difference in performance of the sample groups was approximately 9.6%.

The grand conclusion from all of this work is that the UOP method works and show promise for the IE discipline. It is believed this approach could be expanded to other disciplines inside and outside engineering with similar results.

7.2 Contributions to Literature

This thesis contributed to the literature in several ways by: (i) highlighting the importance of the problem definition process in engineering design from several angles: anthropology, psychology, design, and engineering education; (ii) identifying the need for more tools in the process and several avenues through which to meet that need; and (iii) creating a study to test the hypothesis that the UOP method works (there are few studies done in design which test the efficacy of interventions meant to improve design performance and so this empirical study in itself is also a contribution). Further contributions include (iv) having adapted the GCVS framework from the literature to help with the categorization of open-ended design problems and, (v) creating an initial rough categorization of IE problem types.

7.3 Implications for Instructors

The author would like to end this thesis on a practical note. There are several implications of this work for engineering instructors interested in the practice of teaching engineering. First, instructors should teach with the understanding that their students are used to and prefer textbook exercises over problems. While they prefer what they are used to, they also know that they need to move beyond this to gain “real world” skills that can help them start their career. Second, there are tools out there that instructors can use in order to help move students from completing exercises to defining problems. Depending on the context and resource constraints, one method will be more useful than another. Low-fidelity prototyping is one such tool that will likely be useful in almost any case: low cost and great benefit in understanding one’s client. Lastly, this thesis has shown that the Universe of Problems approach aid problem diagnosis in an undergraduate context. It has shown to work in Industrial Engineering, and the literature shows it works in pure and medical science. For this reason, it is likely that any instructor can incorporate the UOP approach into their classes. They can organize the material they cover in such a way that it places key concepts for students in an expert-like categories and gives students the opportunity to “play” with each model or problem. If students are given these opportunities, they will become more adept at defining problems well.

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APPENDICES

Appendix 1 - The Quality Control Assignment

Introduction to Modelling in Industrial Engineering
Lab Assignment 1

Consider the basic dimensions of quality described on pages 4-5 and the definitions of quality (pages 6-7) in the readings as you perform some quantitative analysis below.

Dimensions of quality: performance, reliability, durability, serviceability, aesthetics, features, perceived quality, conformance to standards.

Definitions: Quality is fitness for use; quality is inversely proportional to variability.

Use the data below to create some basic data visualizations in Microsoft Excel.
These data (simulated) response time for ambulance calls in the city. You are given the date, incident number, and response time. (See news article for some background – there is at least one key piece of information in this article that you will need. Let me know if for some reason you cannot watch or read this article) https://globalnews.ca/news/4850641/nova-scotia-paramedics-ambulance-wait-times/

Create the visualizations I suggest below (the "tasks") from this data and make appropriate comments on the quality of this aspect of our health care system (again, this data is not real but has been simulated by me). In general, we are asking, is there empirical evidence that the system needs to be improved? If this were real data, what would you conclude from it? If you worked for the Ministry of Health would you suggest that your supervisor (if they had the power to do so) further explore the issue of response times or not bother? Does this process seem "under control" or not?

Use the tools from tutorial and from the posted pdf (pages 63-72) to explore this data set and draw conclusions. You can use extra plots or tools as you wish, but as a base line it is a good idea to use the ones suggested in the tutorial and in the book:

- A stem-and-leaf plot
- Time-series plot
- Histogram
- Boxplot
- Any other tools you might find helpful

Notes:

- You can do any additional data grouping/manipulation you may find useful
- State any (and defend why you think they are reasonable) assumptions you may need to make for your analysis

You will be graded on your ability to:

- Be technically correct in your creation of the various plots/visualizations
- Interpret your plots correctly
- Make a convincing argument one way or the other (whether you argue our response system is adequate or needs work).

Here is the raw data downloaded from the (fictitious) Ambulance Response Time database:

Date	incident #	response time
01-Jan-20	1	14.929807
01-Jan-20	2	16.31548199

01-Jan-20	3	13.25020655
01-Jan-20	4	13.73686542
01-Jan-20	5	25.29650084
01-Jan-20	6	3.713053058
01-Jan-20	7	10.80230375
01-Jan-20	8	11.70650581
02-Jan-20	1	27.24521811
02-Jan-20	2	10.12480188
02-Jan-20	3	12.76132551
02-Jan-20	4	11.1979218
02-Jan-20	5	24.11844443
02-Jan-20	6	22.18270274
02-Jan-20	7	8.604387528
02-Jan-20	8	14.42840219
02-Jan-20	9	9.096500842
03-Jan-20	1	32.7760734
03-Jan-20	2	5.251302515
03-Jan-20	3	7.417788179
03-Jan-20	4	27.69650084
03-Jan-20	5	29.19521811
03-Jan-20	6	28.65479011
03-Jan-20	7	29.49521811
03-Jan-20	8	21.05077079
03-Jan-20	9	15.92840219
03-Jan-20	10	8.467788179
03-Jan-20	11	25.29631871
03-Jan-20	12	18.7268819
03-Jan-20	13	27.8124788
03-Jan-20	14	11.7650798
03-Jan-20	15	30.00479011
03-Jan-20	16	24.06734625
03-Jan-20	17	11.01686825
03-Jan-20	18	42.46190412
03-Jan-20	19	27.20623366
03-Jan-20	20	24.20018108
03-Jan-20	21	34.81132551
03-Jan-20	22	21.5228044
03-Jan-20	23	39.6728044
03-Jan-20	24	18.2260734
03-Jan-20	25	20.2778002
03-Jan-20	26	25.56734625
03-Jan-20	27	16.72904793
03-Jan-20	28	21.529807
03-Jan-20	29	9.996318705
04-Jan-20	1	36.16132551
04-Jan-20	2	8.76224479
04-Jan-20	3	18.46132551
04-Jan-20	4	11.1243185
04-Jan-20	5	19.7260734
04-Jan-20	6	30.53047632
04-Jan-20	7	33.15479011
04-Jan-20	8	8.750181081
04-Jan-20	9	18.75650581
04-Jan-20	10	13.59979345
04-Jan-20	11	27.20018108
04-Jan-20	12	15.24650084

04-Jan-20	13	21.26317465
04-Jan-20	14	26.30077079
04-Jan-20	15	12.24631871
04-Jan-20	16	29.38270274
04-Jan-20	17	12.26305306
04-Jan-20	18	31.40623366
04-Jan-20	19	17.24349419
04-Jan-20	20	30.99631871
04-Jan-20	21	29.26190412
04-Jan-20	22	32.93047632
04-Jan-20	23	12.75130251
04-Jan-20	24	35.04650084
04-Jan-20	25	20.02603362
04-Jan-20	26	18.67095207
04-Jan-20	27	40.06132551
04-Jan-20	28	30.69453844
04-Jan-20	29	14.8731181
04-Jan-20	30	43.72160392
04-Jan-20	31	14.770193
04-Jan-20	32	11.89219487
04-Jan-20	33	32.43289821
04-Jan-20	34	30.19219487
04-Jan-20	35	20.77480188
04-Jan-20	36	30.04262261
04-Jan-20	37	13.14922921
04-Jan-20	38	30.34262261
04-Jan-20	39	14.73451801
04-Jan-20	40	26.03686542
04-Jan-20	41	14.18399231
04-Jan-20	42	39.82480188
04-Jan-20	43	50.56190412
04-Jan-20	44	20.99349419
04-Jan-20	45	15.73270274
04-Jan-20	46	39.69521811
04-Jan-20	47	39.84521811
05-Jan-20	1	18.83047632
05-Jan-20	2	20.98546177
05-Jan-20	3	23.7979218
05-Jan-20	4	38.46686825
05-Jan-20	5	#NUM!
05-Jan-20	6	21.9650798
05-Jan-20	7	24.37603362
05-Jan-20	8	19.1721998
05-Jan-20	9	27.3760734
05-Jan-20	10	#NUM!
05-Jan-20	11	17.19453844
05-Jan-20	12	48.07160392
05-Jan-20	13	24.52396638
05-Jan-20	14	27.69561247
06-Jan-20	1	51.46029107
06-Jan-20	2	37.44631871
06-Jan-20	3	33.80077079
06-Jan-20	4	18.21224479
06-Jan-20	5	31.579807
06-Jan-20	6	26.3479218
06-Jan-20	7	52.36029107

06-Jan-20	8	32.029807
06-Jan-20	9	30.53686542
06-Jan-20	10	17.74219487
06-Jan-20	11	29.7760734
06-Jan-20	12	21.4731181
06-Jan-20	13	25.49349419
06-Jan-20	14	23.34979345
06-Jan-20	15	35.16600769
06-Jan-20	16	27.07396638
06-Jan-20	17	23.79979345
06-Jan-20	18	31.88686542
06-Jan-20	19	30.01132551
06-Jan-20	20	20.18399231
06-Jan-20	21	36.50077079
06-Jan-20	22	44.55479011
06-Jan-20	23	45.39586694
06-Jan-20	24	21.24453844
06-Jan-20	25	21.36224479
06-Jan-20	26	49.06132551
06-Jan-20	27	23.19631871
06-Jan-20	28	26.60438753
07-Jan-20	1	30.62327348
07-Jan-20	2	32.19561247
07-Jan-20	3	41.28289821
07-Jan-20	4	33.26317465
07-Jan-20	5	54.6728044
07-Jan-20	6	27.88546177
07-Jan-20	7	44.03047632
07-Jan-20	8	33.47840219
07-Jan-20	9	38.90077079
07-Jan-20	10	29.64586694
07-Jan-20	11	31.27603362

Appendix 2 - The Inventory Assignment

Introduction to Modelling in Industrial Engineering
Lab Assignment 2

Your clients own a coffee shop called “The Jittery Jolt” and they have included data on their daily sales below. It is the exact same sales they had last year at each date, but they are using last year’s data to forecast what they think this year’s demand will be. Some more information you may wish to know:

- On average, a coffee shop in this country sells 230 cups a day
- The Jittery Jolt currently orders 20 bags of coffee at a time whenever they need them but wonder if they are wasting money either on holding costs or shipping costs

You are allowed to assume:

- The demand listed below for a certain day is EXACTLY how many coffees will be sold that day (likely not true, but these are the numbers from last year and we assume that we will have similar demand this year)
- Assume that you order the amount you need at 4am each morning and it always arrives by 6am when you open your shop
- There is currently enough stock (the next workday is January 1st) to serve 500 coffees
- You can order as many bags as you want – but the delivery charge is $2.50 regardless of how many bags you order
- The cost of keeping extra bags on hand is $0.20 for each bag of coffee per day (cost of having to rent a bigger space, the time it takes to store and retrieve the bags, etc.)
- Each bag of coffee can make 41 coffees (approximately)
- The company has a policy of never running out of coffee for fear of losing customers

Questions:

1. Determine the cost of your client’s current inventory policy for the month of January 2021 according to the data below. (Their policy is that they order 20 bags of coffee at 4am on any day they predict they will not have enough coffee.)
2. Now come up with two other ordering policies (guess and test) to see if you can develop an ordering policy for the January data to save them money (i.e. see if you can get a lower total cost than they have).
3. Now try and use the idea of EOQ to see if that can get an even better result (lower total cost).
4. Comment on which policy is best and why.
5. Now compare the total costs you calculated with the 4 different ordering policies (the client’s default policy, two of your “guess and test methods”, and finally the EOQ method) with the theoretical Total Cost according to the formula for those same 4 policies. Are they different? If so, give at least 3 reasons why this may be the case.
6. Plot the actual total costs vs. order quantity for your 4 policies. Does the curve look anything like the Total Cost curve on Figure 3.5 of the readings? Why or why not?
7. Finally, tell your client, in everyday language, what their inventory policy should be and how they should go about ordering their coffee. Be as precise as possible since the owner has admitted that he isn’t so good with details and isn’t sure what to do if you were to just give him some number like EOQ = 20 and say that this was the “answer.”

date	coffees sold per day
01-Jan-21	268
02-Jan-21	167
03-Jan-21	194
04-Jan-21	250
05-Jan-21	216
06-Jan-21	296
07-Jan-21	273

08-Jan-21	213
09-Jan-21	144
10-Jan-21	301
11-Jan-21	221
12-Jan-21	216
13-Jan-21	188
14-Jan-21	279
15-Jan-21	250
16-Jan-21	204
17-Jan-21	344
18-Jan-21	215
19-Jan-21	239
20-Jan-21	233
21-Jan-21	233
22-Jan-21	268
23-Jan-21	281
24-Jan-21	188
25-Jan-21	146
26-Jan-21	231
27-Jan-21	161
28-Jan-21	257
29-Jan-21	250
30-Jan-21	130
31-Jan-21	194

Appendix 3 - The Process Flow Assignment

Introduction to Modelling in Industrial Engineering
Lab Assignment 3

You have been asked to improve the process at a factory that makes Kerosene cans. (see https://www.youtube.com/watch?v=XUs5xkJF0vs – please let me know ASAP if you cannot access this video from your location. I will find a way to give you access if you can let me know before Monday February 8th, 8pm). They say that they believe that they could improve their process somehow but aren't sure exactly how. They want you to go in and see what you can find.

Apply all the process analysis tools that you can to this situation (you will likely have to watch the video several times). This includes but is not limited to (see posted readings and tutorials):

- Operation process chart
- Flow process chart
- Flow Diagram
- Value Stream Map

Although these diagrams are quite similar to one another, going through this process a few times with slightly different tools has benefits as well as trying to understand which kind of chart may be most appropriate for this scenario.

Note: you do not have perfect (information)! Assume you only have access to the video with regards to any data you can collect from this factory. In this case, you will have to make assumptions (or do some quick "research" online to help you with and guesses) regarding things like:

- Length of shifts
- How many employees work at a time
- How many employees work at each station
- Their budget/ ability to hire more workers
- If they produce in batches or just in single pieces
- Approximate sizes of equipment and size of this part of the facility

Report back to your boss regarding the following questions and comments:

- Which chart is most appropriate for this particular scenario in your opinion?
- What is your best guess/approximation of this factory's daily output? Give different guesses based on different assumptions such as the work days are 8h, 12h, or 24h. etc.
- Can you identify any areas of waste in the production process? (Any kind of waste, time, materials, etc.)
- Potential changes you could or would make to the process. Try an make educated guesses as to how much the changes may cost them and save theml. Brief web research is ok to use here if you need some benchmarks re: costs of raw materials, machinery, labour, and so on.
- Health and safety concerns; suggestions for improvement if you have any
- Ethical issues you are concerned about (if any)

Appendix 4 - The Queuing Assignment

Introduction to Modelling in Industrial Engineering
Lab Assignment 4
(Courtesy of Mr. Simranjeet Singh Chadha)

Question 1

ABC airport has two runways, one for take offs and one for landings. For a particular day, arrival times of aircrafts are provided. These arrival times denote the time when airplanes are requesting to land (measured in minutes past Midnight of February 22, 2021). Data on receiving clearance and time required to land is also provided. A plane must be cleared for landing and then actually land before clearance can be given to another plane to land. Awaiting airplanes must circle the airport airspace until they are cleared to begin their descent.

The Airport Safety Manager has decided upon two criteria to maintain the safety regulations for landing and prevent congestion: (1) the average # airplanes waiting to receive clearance should not exceed 1.75 planes; (2) the average waiting time before landing clearance should be less than 4 minutes.

a) State which queuing model you are using to depict the current state and why it is reasonable to use it.
b) According to your model, state how well are the key criteria are being satisfied (or not).
c) Airport management is thinking of adding a second and perhaps a third runway to enable simultaneous landings. If the service rate remains about the same, will they achieve their goals? In which scenario?
d) Each new runway will cost about $150 million. If the landing fee for each plane is about $250, what will the increase in arrivals to the airport have to be in order to pay for one new runway in 5 years? Two new runways? On the other hand, if traffic remains the same even after adding one or two runways, how much will they have to increase their landing fees to pay for the new runways (1 or 2) in 5 years?

Question 2

Consider a fast-food restaurant drive through. You as a Manager decide to look at the past data of arrival times and service times and analyze the system in terms of how it functions as a queue. The company uses the following criteria to make sure that their drive-through service is up to standard:

- Wait time for a customer before getting the chance to order should be less than 2 minutes; and, utilization of servers should be at least 50%.

Due to COVID, drive throughs are gaining more attention than dine in. See the associated Excel file for the raw data and answer these questions:

a) State which queuing model you are using and why it is reasonable to use it.
b) Given this historic data, are you currently meeting standards?
c) It is forecasted that the arrival rate might increase by 25%. Can you meet these criteria given how this system is currently operating? Explain why or why not.
d) Your manager thinks she may have to hire another person but would prefer not to. She thinks that if the servers were able to serve 10% faster they would be able to avoid hiring someone. Is she right? Explain why or why not. Does she have a good idea? How much faster (by %) will the servers have to serve in order to meet the criteria (if it is indeed possible to meet the criteria by simply going faster).

Appendix 5 - The Human Factors Assignment

Introduction to Modelling in Industrial Engineering
Lab Assignment 5

For this week's assignment, please do the following:

- Fill out the checklist for a given app/website/interface of your choosing. You can use an app or web-page, but it could be any interface – perhaps some interface you have at work that is relatively uncommon, etc.
- Include all relevant screen shots of your app/web page (and web address) so we can see the item(s) you were evaluating
- List 3 especially poor parts of the interface your chose. Give reasoning as to why they are good from the principles suggested in the lecture slides/readings
- List 3 especially good parts of an interface; justify why these are good designs by citing the good use of the principles suggested in this chapter
- Include 10 sketches (or some other rudimentary way of explaining your concept) of how your suggestions would look/work. I encourage pencil-and-paper prototypes. Using your stylus and ipad or drawing app is of course fine
- Please evaluate only one interface if possible.

Appendix 6 - The Linear Programming Assignment

Introduction to Modelling in Industrial Engineering
Lab assignment 6
(Courtesy of Mr. Simranjeet Singh Chadha)

These assignments enable hands-on experience for developing and estimating solutions for decision-making problems using mathematical models. The objective of this assignment is to develop an aptitude to comprehend the problem statement and use the data provided to develop a relevant mathematical model and approximate solutions. (Note: methods for finding optimal solutions will be given in the classes OR I and OR II for IE students: Fall 2021 and Summer 2022 respectively. For those interested, multiple tools are available to solve the model e.g. (https://opensolver.org/); GUSEK (http://gusek.sourceforge.net/gusek.html#1), MPL (http://www.maximalsoftware.com/); Python and other coding languages.)

However, for the purposes of this assignment you are only responsible for learning how to describe the problem in terms of its mathematical equivalent and estimating lower bounds, upper bounds, and a good valid solution. We will be using Microsoft Excel for these tasks.

For the following six case studies borrowed from Hillier et al., please create the associated linear models, estimate upper and lower bounds for your solutions, and come up with at least one valid solution for your model.

Appendix 7 - Case Studies

All four of the following case studies had the same seven short-answer questions associated with them (included at the end of this appendix).

Problem Definition Assignment 1 of 4

The purpose of these 4 assignments is to give you practice recognizing typical problems in Industrial Engineering.

Read the following project summary and answer the questions below:

The Dartmouth-Halifax Hospital is the only hospital in Nova Scotia that is legally permitted to diagnose and treat a particular type of heart-disease (HD) patient. They can use Treatment A or Treatment B. Some data was collected regarding how quickly HD patients were treated: imaging time (how long it took between when the patient arrived at the hospital to when images were taken), Treatment A Time (time between arrival and when given Treatment A), and Treatment B Time (time between arrival and when given Treatment B). Some basic statistics (e.g. average times) showed that the hospital was not meeting nationally mandated targets. if Treatment A is given, it should be within 20 minutes of arriving at the hospital. If Treatment B is given, it should be given within 50 minutes of arriving at the hospital.

An important part of successful treatment of patients is, of course, recognizing a patient who may have had or is having a heart attack. Either paramedics or Emergency Department doctors must recognize the signs. As soon as a health-care professional suspects a heart attack the Heart Attack Protocol (HAP) is executed which tells them what measurements to take, what diagnosis to tentatively suggest, and what treatment may be most effective (if any). Various hospital staff and administrators had concerns that different patients experienced a different quality of care depending on if the protocol was activated in the ambulance or hospital, and if the patient arrived before or after regular business hours.

While students were learning more about the admission and treatment methods for these patients, different stakeholders were suggesting various solutions to what they perceived to be the problem. Some stakeholders wanted to change how various steps in their treatment were implemented, others wanted to buy new equipment, hire new people, or change current treatment policies.

In October and November students used various industrial engineering tools and methods to describe and analyse the steps patients went through to identify areas for improvement before some potential solutions were generated in January and evaluated in February. (At this point a real project summary would go on to recap the tools the students used to discover issues with the system, how they analyzed data and formed conclusions, and finally their recommendations to the client on how they should make changes to improve the system).

Problem Definition Assignment 2 of 4

The purpose of these 4 assignments is to give you practice recognizing typical problems in IE.

Read the following project summary and answer the questions below:

The “drop-off” team at NS Natural Valley Farm (NSNVF) is responsible for making sure that animals are taken care of properly before they go through some kind of process. This process is typically taking them to be checked by a veterinarian or to be “harvested” – that is, taken to the butcher or taken to be milked. It is a small farm, so there are no automated processes for things such as milking. Regardless of which process is required, someone has to take animals (cows, goats, etc.) from their stalls or the field and bring them to the main facility where they undergo the appropriate procedure (being seen by a vet, milked, or butchered).

There are “walkers” that take the animals from the fields/stalls to the main facility and sometimes have to “babysit” the animal so it won’t get into trouble before it starts a particular process (being seen by the vet, etc.). The milking and butchering processes are quite straight forward and seem to be working well. The vet’s process is very complicated and NSNVF respects her expertise and doesn’t want to change how she diagnoses and treats animals right now. However, employees started to notice in the last year or so that sometimes the “walkers” had to stay with the animals for a long time before they were seen. This meant that they could not go and get the next animal that needed to be ushered in and it seemed to slow down the process. Sometimes this meant that problems would begin to worsen with animals out in the field (animals who need to get milked can’t be delayed too long, sick animals would get sicker if left in their stalls too long, and so on). Not to mention, once in a while, there would be a large group of walkers with their animals waiting for their procedure. These groups, as one could imagine, could become chaotic or difficult to manage.

Last year, NSNVF decided to implement a “drop-off” team which was there to take care of the animals while they waited for their appointments; this way, the “walkers” could go and fetch another animal and thus speed up the process. The consultants on this project found that with the drop-off team the walkers were able to cut their normal drop-off time in half (50% savings) and use their time to go and get another animal instead of waiting around. The time it takes to drop an animal off is never exactly the same: with the old system the average time to drop-off was 9.2 minutes and 95% of drop-offs were completed within 15 minutes. Now with the drop-off team, the average time to drop off is 5.5 minutes and 95% of drop-offs take less than 7.5 minutes.

While the students and farm managers think they should be happy about this result, they aren’t sure. They want to know the effect of the drop-off team on the overall effectiveness of the system such as animal throughput and also if hiring the extra people needed to make the drop-off team work was worth it. The students are wondering what they should do next to better understand the system and improve it for their client.

Problem Definition Assignment 3 of 4

Hascap Industries is a relatively new company and has only existed for 10 years. They are experiencing growing pains as they increase their number of employees as well as their production capacity. They are a specialized manufacturing company and fabricate custom masks for the construction industry (designed to protect wearers from sawdust, paint fumes, etc.) and the medical industry. They have clients all over the country as well as the world; however, most of their customers are in North America.

They are experiencing a few problems right now: they are having trouble training new employees to follow standard operating procedures, and even developing those standard operating procedures in the first place. Many employees do their particular part of the manufacturing process the way that seems best to them since when the company was smaller they had a lot of freedom to do this. Managers are also having trouble keeping enough cash on hand to enable day-to-day purchases and operations.

A big issue has been creating and implementing their production plan. They are finding it difficult to make the right amount of product. If they make too little, their clients get upset because it can take a long time to fulfill orders. But, if they make too much, they have a lot of extra financial resources tied up in raw materials and finished goods. They don’t mind so much storing things in the warehouse – they have lots of space. What they don’t have is a lot of extra cash to spend on materials when they could use it for paying employees, purchasing new buildings and equipment, and so on.

The production plan is complicated since they have some old clients, but since they are growing so fast they have a lot of new clients as well – and they are spread all over North America so shipping to all of these places is costly and difficult to manage. If this weren’t challenging enough, they also have several suppliers: this means that they also have to coordinate with many different companies to make sure they have the right materials on hand at the right time to make their masks. Lastly, they also have to deal with some returns. Masks can be very expensive and if clients are not happy or find a quality issue, they are told they can return the item for a full refund. They are expensive enough that right now it seems it is worth taking the item back and fixing it and re-selling instead of just allowing the client to keep it as-is or throw it out. All of this is becoming to be too much for their production manager who has only had the job for two years and who has had no other relevant work experience before this. They have reached out to Dalhousie to see if a student team can help them come up with some ways of managing this issue.

They are hoping to find some way to be able to serve as many customers as possible as quickly as possible without putting themselves in a place where they are in so much debt that they have to re-mortgage their property – or worse – file for bankruptcy. They never thought they would be in this predicament since they are making a great income, it's just an operational issue with regards to how to use their finances well.

Problem Definition Assignment 4 of 4

The purpose of these 4 assignments is to give you practice recognizing typical problems in IE.

Read the following project summary and answer the questions below:

Angel Hills Fire Department in the city of Angel Hills, Nova Scotia is concerned that they are not meeting the response times required by various governing bodies. Every particular station is required, by law, to exit their building within 75 seconds of receiving an emergency call. They have to exit the building with the proper number of firefighters (which will depend on the type of vehicle) in a registered vehicle and with each crew member wearing the appropriate safety gear (and worn properly so that it can work as intended). The Fire Department Headquarters (FDHQ) is worried that many of their stations are not able to meet this standard.

The FDHQ is not sure what the best way to tackle this problem is so they have asked for some consultants to come in and take a look at their operations. The student consultants had some initial meetings with the head office and firefighters. The FF are feeling the pressure from head office to meet these times and feel they are unreasonable; however, head office feels as though the employees should be meeting the targets already and is not sure why they are not currently doing so. They are somewhat suspicious that this is some kind of strategy to ask for more finances or resources as another collective bargaining agreement has to be made between firefighters and Fire Department management in about six months.

Some discussion with the FF shows that they think there are several issues. Some say that their safety gear is getting old and takes longer than newer gear to put on; some other FF say that the issue is that their shifts are too long and the only time they are late to leave the station is when everyone is asleep. Still others say that the real problem is that many of the fire stations are old and have been renovated several times and the renovations haven't always been for the best – a lot of "make-shift" changes were made without realizing the impact they would have on response times. For example, female dorms were added into many of the older stations in the 1980s and 1990s which meant that people were far away from the fire engines when a call was received. Others complain that things that seem silly make a big difference – various doors sometimes stick and/or are hard to open, hallways are long and narrow so are hard to rush through, and so on. Some people in different stations complain as well that the kitchen and the common room are too far away from the garage (and therefore the fire trucks) while less-important and rarely-used things such as storage rooms and furnace rooms are very close to the garage. The head office is aware of some of these issues. While they are concerned about the cost of renovating all of their stations, they have recently secured funding to renovate about a dozen old stations and build six new ones near the growing suburban areas of the city.

Both the FF and the FDHQ are hopeful the student consultants will be able to come up with something to help them out by April so they can mitigate the problems they are seeing.

Short-answer questions asked at the end of each case study:

1. What is/are the major goal(s) of this project?
2. What are the key variables and parameters (things only, not persons for this question) in this system?
3. Who are the key stakeholders (persons or roles) in this system?
4. What are some of the most important constraints in this system?
5. What are some potential strategies open to students for moving forward in this project? In other words, what are key Industrial Engineering tools that may help uncover issues with the system? List applicable tools and a brief description of why they would be a good idea to use.
6. What sort of Industrial Engineering problem is this best categorized as? (Inventory, process flow, human factors/ergonomics, queuing, data management, facilities design, quality control, or something else? Or nothing?)
7. Why do you think this problem should fit into this category?

Appendix 8 – Models Summarized in terms of GCVS (from Lecture Slides)

The Quality Control Model

- Goal: reduce variability in a process
- Constraints: the specifications given by the design team/documents; budget; machine/human ability
- Variables: mean and standard deviation of characteristics of our products are key here
- Strategies: Data measurement and plotting to help identify "assignable causes"

The Inventory Problem

- Goals: minimize total costs due to holding, ordering, and being short of inventory
- Constraints: space for holding inventory, total budget
- Variables: when to order, how much to order (Q),
- Strategies: Vary Q, ABC (pareto) analysis which helps to focus us on the most important SKUs, forecasting to predict demand as accurately as possible, speak with suppliers about trying to minimize lead time, create standard operating procedures to keep on top of inventory current levels, proper use of Inventory software

The Process Flow Problem

- Goals: Understanding a process and its details; Identifying areas for process improvement
- Constraints: physical or rule-based; Physical constraints to movement of people or product (Weight, walls, customer requirements, requirements of machinery, etc.) Rule-based constraints: Safety, policies, legal obligations
- Variables: Distance, time, inventory, queue length, etc.
- Strategies: Measure current process with different tools; propose alternate process and guess at performance; Micro strategies: reduce travel times, reduce process times, and so on

The Queuing Problem

- Goals: minimize time in queue/system; minimize # of customers in line/system; maximize server utilization; minimize $ spent; determine trade-off between quicker service and lower expense (Gross et al., page 9)
- Constraints: service speed, capacity of queue/system; number of servers, queue discipline, etc.
- Variables: arrival rates, service rates, # of servers, queue discipline, how many stages in the service, etc.
- Strategies: gather data and confirm arrival and service distributions, use formulae when possible, use simulation tools only if models are too complex to solve analytically

The Human Factors Problem

- Goals: to maximize human performance, human safety
- Constraints: cognitive abilities, physical abilities, emotional abilities
- Variables: # of errors, workload on users, stress on users, fatigue, etc.
- Strategies: study users in their key tasks; re-organize tasks to make them easier, faster, safer to complete; design for recognition of anomalies/ unsafe conditions; design for various populations, and so on

The Linear Programming Problem

- Goals: optimize business decisions
- Constraints: total available resources, minimum levels of acceptable service (of some kind - e.g. radiation or customer service), available flow/cost of flow/travel
- Variables: decision variables: how much, when, where to produce, buy, assign …
- Strategies: Non-technical: understanding stakeholders well, understanding system dynamics, estimating parameters, gathering data, introducing data tracking systems, creating and refining models. Technical: Linear, Integer, mixed, Non-linear programming. Heuristic approaches.

The Facilities Design Problem

- Goals: minimizing total facility costs (often focus on material handling)
- Constraints: capital budget for a new building, aspects of facilities that cannot be changed; exterior shape; min/max square footage for particular rooms; safety/fire code regulations; personnel capacities for rooms, etc.
- Variables: key ones here are “flow distance” between entities
- Strategies: gather flow data, translate into activity-relationship diagrams, create string diagrams; consider multiple solution prototypes by hand or with aid of computer programs; evaluate with flow-distance score

Appendix 9 – Research Ethics Materials

Recruitment plan:

The RA will recruit in all courses for consistency and so that students will not feel coerced into taking part in the study due if I were to recruit (in courses where I am or am not an instructor I am recognized as a faculty member in the department and therefore there is a power distance between me and the students). In IENG 2201, IENG 4480, and IENG 4852, the RA will introduce the study as close to the second synchronous class of the semester that is possible that is held online in February. For IENG 4852, since it is a year-long course, (Sept 2020 to April 2021), the same recruitment methods will apply although it will be the first or second class of the second *half* of the year-long course instead of the first or second synchronous class of that course. For the IENG 3345, the RA will recruit approximately in the 2nd synchronous class of May 2021. Note the process will be the same whether I am the instructor or not. The RA will read the following blurb (which will also appear on Bright Space and in an email sent to each student via the Bright Space course page):

This course is part of a research study that seeks to understand if presenting the "big picture" view of common Industrial Engineering problems can help students design better solutions in industrial engineering. The project will analyse the results from four assignments in this class each worth 2.5% of your grade.

*If anyone wishes to participate in this study, please simply click on this link ***link will be placed here *** and fill out the short survey and consent form (5-10 minutes). You will be enrolled in the study if and when you decide to submit your online form. The instructor of the course will not be aware of who is in or out of this research study. The RA will collect the assignments and assignment grades of those who wish to be in the study (after course grades are released at the end of the semester), a short survey that you will fill out if you agree to participate (please see announcement and link to the survey on BrightSpace), and then remove your name and B00# before sending the Principal Investigator (Mr. Scott Flemming) the compiled results. Participation in this study is completely voluntary and your grade in this course will not be different regardless of whether you participate or not. No analysis will be completed until final grades for this course are released. Finally, if you do decide to participate in the study, you can decide to remove yourself from the study at any time before the final grades are released (May 15th for Winter Semester and September 15th for Summer Semester) by emailing probDef@dal.ca*

The announcement on each course's BrightSpace (BS) page will be the following:

As stated during lecture, this class is a part of a research project. Please fill out this brief survey if you consent to having some of your assignments collected and analysed along with your answers to the following questions.

The RA will then ask if there are any questions, and after the questions are answered leave the room (either virtual online room or actual room). At this point the RA will remind them that they can see the announcement on BS or the email that will be sent to them if they wish to participate. They can also be instructed that, if, for some reason the RA is not able to answer a question to their satisfaction, they can contact the principal investigator at scott.flemming@dal.ca

There will be no screening procedures other than those detailed in 2.3.1 to ensure a student from IENG 3345 has not already completed these assignments in IENG 2201.